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Master Thesis

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Topic: Development of a Python Tool for Calculating Loss Maps of Traction Gearboxes for Electric Commercial Vehicles

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II List of Symbols and Abbreviations

Symbol	Unit	Description
b		Face Width of the Gear
d	mm	Pitch Diameter
F_t	N	Tangential Force
i		Gear Ratio
L		Load Dependent Meshing Losses
m	mm	Module
P_{drag}	W	Load Independent Drag Losses
P_{in}	W	Input Power
P_{out}	W	Output Power
T	Nm	Torque
t_{drag}		Drag Torque
t_{in}		Input Torque
t_{out}		Output Torque
Y		Lewis Form Factor
β	°	Helix Angle (Helical Gears)
η_{ld}		Load Dependent Efficiency
λ		Loss Factor
σ	Pa	Bending Stress on Gear Tooth
$\sigma_{material}$	Pa	Allowable Stress of the Material
ω	rad/s	Angular Velocity

Abbreviation	Description
AT	Automatic Transmission
CVT	Continuously Variable Transmission
DCT	Dual-Clutch Transmission
E-axle	Electric Axle
EM	Electric Motor
Eq.	Equation
EV	Electric Vehicle
JSON	JavaScript Object Notation

Symbol	**Unit**	**Description**
NRMM		Non-Road Mobile Machinery
PGS		Planetary Gearset
RPM		Revolutions Per Minute
SF		Security Factor
SG		Simple Gear
WLTC		Worldwide Harmonised Light-Duty Vehicles Cycle

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1 Introduction

The global shift towards electric traction drives offers significant potential for advancing sustainable transportation within the commercial vehicle industry[1, 2]. While the electrification of passenger cars has progressed substantially, the commercial vehicle sector, including trucks, buses, and non-road mobile machinery (NRMM), remains in the early stages of this transition. As a result, the solutions available for commercial vehicle electrification are neither as widespread nor as standardized as those developed for passenger cars.[3]

This disparity arises because commercial vehicles face distinct challenges compared to passenger cars. They must operate reliably under a wide range of conditions and applications, requiring higher power outputs and robust performance in various environments. These complexities make it difficult to apply the approaches used in passenger car electrification directly to commercial vehicles.[4]

The need for innovative and tailored solutions to support the electrification of commercial vehicles is becoming increasingly critical. This thesis contributes to this effort by addressing one of the key technical challenges in this area.[5]

1.1 Motivation and Objective

The electrification of commercial vehicles presents a range of complex challenges, particularly in the area of gearbox design and optimization[6]. Efficient gearbox design is essential to ensuring the reliability and performance of electric drivetrains, yet existing simulation tools are often inadequate for addressing the specific needs of commercial vehicles. These tools typically require detailed design parameters, which may not be available during early-stage development. Additionally, they lack the flexibility to accommodate the diverse operational conditions that characterize commercial vehicle applications.[7]

This gap in available tools significantly limits the ability of engineers to rapidly iterate and refine gearbox designs, slowing the overall development process. Consequently, the need for a simulation tool that can operate effectively with limited data and provide accurate results across a variety of gearbox configurations is derived.[8]

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[1] cf.Lajunen et al. (Electric and Hybrid Electric Non-Road Mobile Machinery – Present Situation and Future Trends), 2016, p. 172.

[2] cf.Beia Spiller, Nafisa Lohawala, and Emma DeAngeli (Medium- and Heavy-Duty Vehicle Electrification: Challenges, Policy Solutions, and Open Research Questions), 2023, p. iii.

[3] cf.Christopher Pohlkamp, Anita Oh, Paul Nguyen, Julien Bert (The Future of Buses and Light Commercial Vehicles Is Electric), 2022, p. 3.

[4] cf.Lajunen et al. (Electric and Hybrid Electric Non-Road Mobile Machinery – Present Situation and Future Trends), 2016, p. 172ff.

[5] cf.Beia Spiller, Nafisa Lohawala, and Emma DeAngeli (Medium- and Heavy-Duty Vehicle Electrification: Challenges, Policy Solutions, and Open Research Questions), 2023, p. 1.

[6] cf.Lacock et al. (Electric Vehicle Drivetrain Efficiency and the Multi-Speed Transmission Question), 2023, p. 1.

[7] cf.Borsboom et al. (*Control and Design Optimization of an Electric Vehicle Transmission Using Analytical Modeling Methods*), 2022, p. 2.

[8] cf.Schumacher et al. (Design, Simulation and Optimization of an Electrical Drive-Train), 2021, p. 390.

In response to these challenges, this thesis focuses on the development of a Python-based tool designed to calculate loss maps and other characteristic parameters for traction gearboxes used in electric commercial vehicles. By enabling scalable and precise simulations of gearbox characteristics, this tool will facilitate the efficient design of various drive concepts. Streamlining the simulation and sizing processes will empower manufacturers and engineers to explore and evaluate different gearbox configurations, supporting the development of optimized electric drivetrains that meet the unique requirements of commercial vehicle applications. Ultimately, this work will contribute to accelerating the transition to sustainable transportation within the commercial vehicle sector.

1.2 Thesis Structure

This thesis is structured to systematically address the challenges in the electrification of commercial vehicle gearboxes, from understanding existing technologies to developing and validating a new simulation tool. The chapters are organized as follows:

- **Chapter 2: State of the Art and Literature Review** – This chapter provides a comprehensive review of current research on gearboxes for electric commercial vehicles and existing loss calculation models. It identifies key gaps in the literature that justify the need for a new tool capable of efficient simulation and analysis of gearbox characteristics.
- **Chapter 3: Architectural Concept and Design of the Tool** – Building on the gaps identified in the previous chapter, this chapter details the architectural concept of the Python tool. It includes the design and implementation strategies to ensure the tool's flexibility and accuracy.
- **Chapter 4: Implementation of the Tool –** This chapter outlines the methodology used in the development of the tool, building on the architectural concepts introduced in Chapter 3. It describes the key components involved in the tool’s structure, including the input module, the loss calculation methods, and the gross sizing algorithm. The chapter also explains how the data is processed, how the sizing and loss models are executed, and how the results are generated and displayed.
- **Chapter 5: Validation of the Tool –** The results of validating the tool are presented in this chapter, including case studies that demonstrate its practical application. The analysis focuses on the tool's performance in simulating loss maps and other key parameters under various scenarios. The chapter includes a discussion on how the sizing estimates contribute to the overall feasibility of the gearbox designs explored.
- **Chapter 6: Summary and Outlook –** The final chapter provides a summary of the key findings, emphasizing the tool's contributions to early-stage gearbox design. It also outlines potential improvements and future research directions to extend the tool's capabilities for evolving transmission technologies.

2 State of the Art and Literature Review

Building on the challenges outlined in Chapter 1, the electrification of commercial vehicles requires an in-depth understanding of gearbox configurations and their impact on drivetrain efficiency. This chapter reviews the current state of gearbox technologies, focusing on the transmission systems used in electric commercial vehicles and NRMM. By examining key aspects of gearbox topology and reviewing the available research on gearbox loss models, this literature review lays the groundwork for developing an efficient simulation tool aimed at accurately calculating gearbox losses and supporting early-stage transmission design for electric powertrains.

2.1 Introduction to Gearbox Topology

To develop such a tool, it is essential to first understand gearbox topology, as it serves as the foundation for analyzing how different configurations might affect the system's performance. As the following chapter will show, due to the novelty of this field, theoretical knowledge on gearbox configurations is relatively scarce. Therefore, the approach begins with the definition of gearbox topology through basic literature exploration, aiming to identify gear types, arrangements, and other characteristics essential for a comprehensive description.

A gearbox topology is fundamentally about how the components within the powertrain are connected. As noted in existing literature, "a topology refers to the layout in which the components in the powertrain are connected to each other."[9] This layout dictates the interaction between gears, shafts, and other elements, influencing the overall efficiency and performance of the gearbox.

2.1.1 The Function of the Gearbox

Understanding the function of a gearbox is crucial for comprehending its topology. As described, "The function of a gearbox is to transmit rotational motion from a driving prime mover to a driven machine. The driving and driven equipment may operate at different speeds, requiring a speed-increasing or speed-decreasing unit. The gearbox therefore allows both machines to operate at their most efficient speeds. Gearboxes are also used to change the sense of rotation or bridge an angle between driving and driven machinery."[10] This function not only defines the purpose of the gearbox but also shapes its design, including the specific topology used.

[9] cf.Verbruggen et al. (Electric Powertrain Topology Analysis and Design for Heavy-Duty Trucks), 2020, p. 4.
[10] cf.Lynwander (Gear Drive Systems: Design and Application), p. 14.

2.2 Key Aspects Defining Gearbox Topology

This section outlines the key aspects that define gearbox topology, providing the framework for describing and identifying gearbox configurations in electric commercial vehicles and electric NRMM. These aspects are crucial for developing a comprehensive understanding of gearbox topology within the context of electrified transportation.

The gearbox configuration chosen for a given application is most strongly influenced by three parameters:[11]

- Physical arrangement of the machinery
- Ratio required between input and output speeds
- Torque loading (combination of horsepower and speed)

These primary parameters form the foundation of gearbox topology. Additionally, understanding the specific type of mechanical power transmission and gear type selection further refines the design considerations for a gearbox.

2.2.1 Physical Arrangement

The physical arrangement of the gearbox defines its topology. The location of the driving and driven equipment in the mechanical system defines the input and output shaft geometrical relationship. Shaft arrangements can be parallel offset, concentric, right angle, or skewed.[12] Each arrangement affects the design, efficiency, and power transmission pathways within the gearbox.

2.2.2 Gear Ratio

The gear ratio plays a crucial role in determining both the mechanical advantage and the operational speed of a gearbox. Although gearing can theoretically achieve unlimited reduction or speed-increasing ratios, high ratios tend to require more complex component arrangements. In a simple gear mesh, ratios typically range from 8:1 to 10:1. The speed reduction or increase corresponds to the ratio of the pitch diameters of the larger gear and the pinion, or alternatively, the ratio of their respective numbers of teeth. Exceeding a 10:1 ratio may introduce stress or geometric limitations on the pinion. For higher ratios with parallel shaft gearing, multiple stages of gear meshes are combined.[13]

An efficient method of achieving high reduction ratios in minimum space is the use of planetary gearing[14]. Which will be discussed in more detail later in this section.

[11] cf.Lynwander (Gear Drive Systems: Design and Application), p. 14.
[12] cf.Lynwander (Gear Drive Systems: Design and Application), p. 14.
[13] cf.Lynwander (Gear Drive Systems: Design and Application), p. 19.
[14] cf.Lynwander (Gear Drive Systems: Design and Application), p. 19.

2.2.3 Torque Loading

Torque loading determines the required size and strength of gearbox components by defining the forces exerted on the gear teeth. Specifically, the torque on a given gear generates a tangential force at the tooth contact point. This tangential force is critical for calculating the stresses on the gear teeth, which in turn influences the sizing of the gears.

The size of gearbox required for a given application is dependent primarily on how large the gear pitch diameters and face widths are. These dimensions are determined on the basis of tooth stresses which are imposed by the transmitted tooth load. The tooth load is simply the torque on a given gear divided by the gear pitch radius.[15] This tooth load is directly related to the tangential force on the gear teeth, which must be carefully calculated to ensure the gearbox can handle the operational demands, particularly in high-torque environments like electric commercial vehicles.

2.2.4 Type of Mechanical Power Transmission

The choice of mechanical power transmission method—whether using gears, belts, or chains—significantly impacts the gearbox's durability, efficiency, and design:[16, 17]

- **Gears**: Gears are typically chosen for their robustness and high efficiency, with power transmission efficiencies reaching up to 98 percent. Among the different methods of mechanical power transmission, gears are generally the most durable, though they tend to be more expensive than chains and belts. The increased cost of gears is associated with the higher precision required for their manufacture, particularly when used in applications demanding high speeds, heavy loads, or low noise levels.
- **Belts and Chains**: Belts and chains are often employed in applications where cost-effectiveness, simplicity, and flexibility are prioritized over the high precision and durability that gears provide. Chains are particularly favored in situations where higher load capacities are required, although they may result in increased noise and require more maintenance compared to belts.

2.2.5 Gear Type Selection

The disposition of the axes to be joined by the gear train often suggests the type of gear to choose. If the axes are parallel, the choices can be spur gears or helical gears. If the axes intersect, bevel gears can be used. If the axes are nonparallel and non-intersecting, then crossed helicals, worm and gear, or hypoid gears will work.[18]

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[15] cf.Lynwander (Gear Drive Systems: Design and Application), p. 24.
[16] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 620.
[17] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 782.
[18] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), p. 431.

2.3 Transmission Concepts in Electric Vehicles

After establishing the foundational understanding of gearbox topology, it is now crucial to identify the specific topologies used in transmission systems, particularly in electric vehicles. Transmission systems rely on these topologies to manage power and torque delivery from the motor to the drivetrain.

This section will build on the fundamental knowledge established so far, introducing the basic transmission concepts that are critical for understanding the broader landscape of drivetrain design. The subsequent analysis examines the specific transmission systems used in electric vehicles, focusing on how these systems are adapted and applied to meet the unique demands of electric drivetrains.

2.3.1 Introduction to Transmission Concepts

Now that the defining aspects of gearbox topology—such as physical arrangement, gear ratio, and torque loading—have been established, this knowledge enables a clearer understanding of transmission systems as a whole. With a firm grasp of what constitutes a gearbox topology, it becomes possible to distinguish between different transmission concepts and, later, to identify common gearbox topologies in electric commercial vehicles and NRMM.

Transmission systems are designed to efficiently manage power and torque delivery from the motor to the drivetrain, utilizing the principles of gearbox topology to meet specific operational needs. At this stage, the focus is on introducing basic transmission configurations that are fundamental across all vehicle types, setting the stage for a more specific discussion on their application in electric vehicle drivetrains later in this chapter.

Transmissions can vary significantly in complexity, ranging from simple single-stage systems to more complex multi-stage configurations.

The simplest transmission construction is the **single-stage** transmission (Figure 2.1a): in this form, one gear wheel of each gear pair is mounted on the input shaft or drive shaft and the other gear wheel of the gear pair is mounted on the output or power take-off shaft. A more complex construction involves a counter-shaft arrangement, where the force is transmitted from the drive shaft to the counter-shaft, and then to the output shaft.[19]

In **multi-stage** systems, the transmission ratio changes with each gear pair, and two-stage transmissions (Figure 2.1b) enable a larger overall gear ratio between the transmission input and output than what is possible with a single-stage system. The main transmission of a commercial vehicle generally consists of a two-stage gearbox with countershaft. The disadvantage of multi-stage gear transmissions is that each gear system through which the force flows in the transmission leads to losses, so it is advisable to have the smallest number of gearing stages in the transmission. Precisely this is the advantage of the direct drive gear: no gear systems through which the force flows and hence reduced losses.[20]

[19] cf.Hilgers (Transmissions and drivetrain design), 2023, p. 14.
[20] cf.Hilgers (Transmissions and drivetrain design), 2023, p. 14.

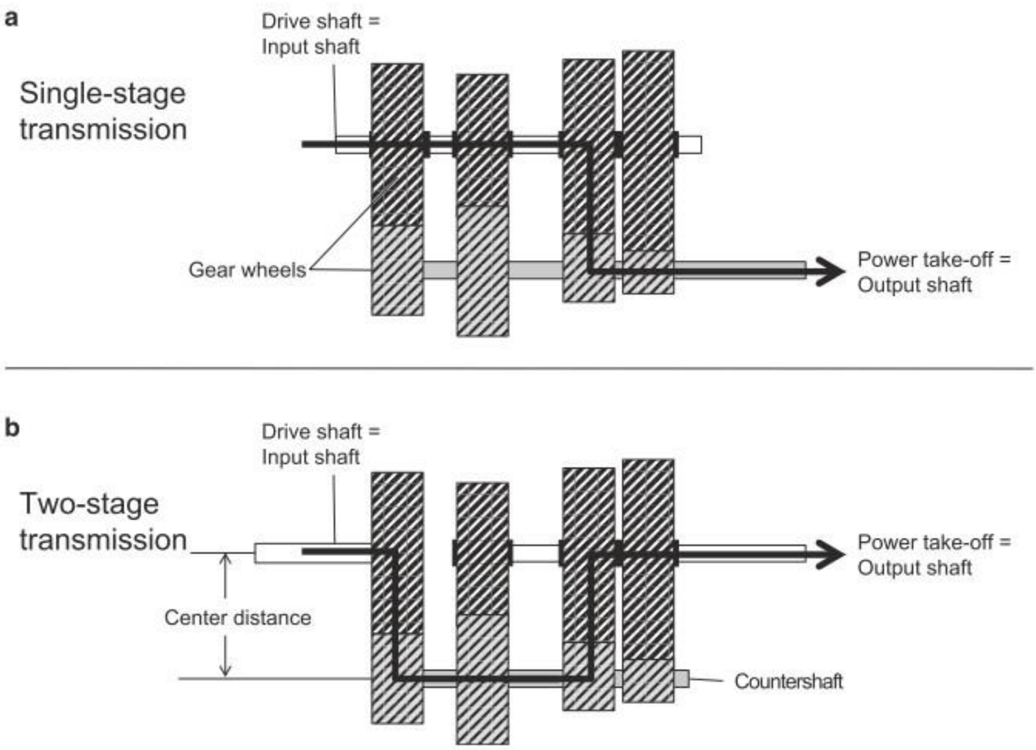

Figure 2.1: The single-stage transmission and the two-stage transmission.

Understanding these fundamental transmission concepts provides the necessary background to explore how transmission systems are applied and adapted in the context of electric vehicles.

2.3.2 Transmission Systems and Configurations in Electric Vehicles

Having introduced the basic transmission concepts, it is now necessary to explore how these systems are adapted to the specific characteristics of electric vehicle (EV) powertrains. In electric vehicle powertrains, the integration of transmission systems is shaped by the unique characteristics of electric motors. Unlike internal combustion engines, electric motors can provide a wide range of torque and operate efficiently across a broad spectrum of speeds. This has led to the adoption of simpler transmission systems in many EVs, though more complex solutions are sometimes employed to optimize performance and efficiency.[21]

An analysis of the existing literature on gearbox and transmission concepts identified key configurations commonly used in electric vehicle transmissions. Although these configurations are widely adopted in electric vehicles, it is important to note that they may not fully address the unique requirements of commercial electric vehicles NRMM, as these applications are not specifically considered.

[21] cf.Crissey (Inside Electric Truck Transmissions), 2020, p. 2.

The following configurations represent different **gearbox topologies** commonly used in electric vehicles, which are responsible for managing the power and torque between the motor and the drivetrain:

- **Single-Speed Transmissions**: A single-speed transmission is the most popular choice for EVs. A single-speed can be made with multi-stage gears, or with a planetary-gear.[22] This simplicity is due to the wide speed range of electric motors, which often eliminates the need for multiple-speed transmissions.
- **Multiple Ratio Transmissions**: Although less common, two-speed automatic transmissions have been proposed for electric powertrain applications. Even though an electric motor can provide a large speed range to satisfy the operational needs of typical cars without the need for a multiple-speed transmission, there are imperfections in this arrangement. Research indicates that a two-speed transmission can fulfill the above purposes and at the same time provide energy savings of at least 5–10% while improving the acceleration, gradability, and top speed of the vehicle.[23]
- **CVTs**: While continuously variable transmissions (CVTs) offer theoretical benefits, traditional CVTs generally do not meet the above requirements because they are usually bulky, expensive, and inefficient. A special design of the transmission is therefore needed.[24]

Additionally, the configurations presented below are examples of **drivetrain topologies** that integrate both the transmission system and the electric motor, optimizing space and efficiency. These differ from gearbox topologies in that they encompass the entire drivetrain architecture, rather than just the gear arrangement:

- **Electric Axles (E-Axles)**: The e-axle integrates the electric motor, transmission, and sometimes the differential into a single compact unit. E-axles are appropriate for use both in hybrid and pure electric drive concepts, offering different performance and design envelope requirements. These units are designed to optimize space and efficiency, making them a popular choice in electric commercial vehicles.[25]

  In commercial vehicles, the axle drive system is a critical component that can be designed in different configurations to meet specific operational needs. There are designs in which the ratio of the ‘axle’ is split between the axle drive and the hub drive. In this case, the term ‘center gearbox’ is used instead of axle drive. The commercial vehicle final drive accommodates the axle drive bevel gears or the worm drive, the differential gear unit and, in the case of multistage axle drives, spur gear sets or planetary sets and the drive-through to the next axle. Axle drives can be subdivided into single-stage and multi-stage systems.[26]

[22] cf.Zhang; Mi (Automotive Power Transmission Systems), 2018, p. 383.
[23] cf.Zhang; Mi (Automotive Power Transmission Systems), 2018, p. 386.
[24] cf.Zhang; Mi (Automotive Power Transmission Systems), 2018, p. 386.
[25] cf.Pfund (Electric Axle Drives – scalable propulsion system for electrified powertrains), p. 2.
[26] cf.Naunheimer et al. (Automotive transmissions), 2011, p. 249.

- **Wheel Hub Motors**: Another innovative solution is the use of wheel hub motors, where electric motors are directly integrated into the wheels. “This option is very attractive, for example, for low-floor buses, although it presents challenges such as increased unsprung masses at the wheels.” In such configurations, the transmission system might be simplified or even eliminated, with power and torque managed directly at the wheel.[27]

2.3.3 Summary

This section has provided an overview of the transmission systems and configurations used in electric vehicles (EVs), focusing on how these systems meet the specific requirements of electric drivetrains. The discussion covered single-stage and multi-stage transmissions, as well as more specialized options like electric axles and wheel hub motors. While continuously variable transmissions (CVTs) were also considered, they are less commonly applied in EVs due to their limitations in efficiency and torque handling. The transmission configurations discussed here reflect a balance between simplicity, efficiency, and the operational needs of electric vehicles.

Subsequent sections will delve into the individual components that make up these transmission systems—gears, shafts, and other critical elements—and analyze their impact on the overall performance and efficiency of EV powertrains. A thorough examination of these components is essential for understanding how various configurations influence drivetrain operation and design.

2.4 Overview of Gearbox Components for Transmission Design

To further support the understanding of gearbox topologies and transmission concepts discussed in the previous sections, it is essential to outline the main components that constitute these systems. These components play critical roles in the functioning and design of gearboxes used in electric commercial vehicles and NRMM, directly influencing the performance and efficiency of the transmission system.

2.4.1 Shafts

Shafts are fundamental elements within a gearbox, responsible for transmitting power and motion. According to traditional nomenclature, “A shaft is a rotating part used to transmit power, motion, or analogic information. It often carries rotating machine elements (gears, pulleys, cams, etc.) which assist in the transmission. A shaft is a member of a fundamental mechanical pair: the 'wheel and axle.'” The distinction between axle and shaft is important, with an **axle** being a stationary member supporting rotating parts, while a **shaft** is a rotating member that supports attached elements.[28]

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[27] cf.Hilgers (Transmissions and drivetrain design), 2023, p. 9.

[28] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), p. 178.

2.4.2 Bearings

Bearings are crucial for supporting shafts and reducing friction within the gearbox. They are classified based on the type of friction they manage, which differentiates them into rolling bearings and plain bearings. Rolling bearings consist of outer and inner rings with tracks, rolling bodies (balls or rollers), and separators that serve to keep the rolling bodies apart. These types of bearings are widely standardized and mass-produced, making them interchangeable and common in various applications.[29]

2.4.3 Clutches and Brakes

Clutches and brakes are components that, despite their similar appearances, serve distinct functions within a gearbox.

"Physically, brakes and clutches are often nearly indistinguishable. If two shafts initially at different speeds are connected by a device to bring them to the same speed, it is a clutch. If one member is fixed and the torque is used to slow down or stop the rotating member, the device is a brake."[30]

- **Clutches**: The primary function of a clutch is to enable smooth and gradual connection and disconnection between two rotating members[31]. The characteristic use is to connect two shafts rotating at different speeds and bring the output shaft up to the speed of the input shaft smoothly and gradually[32].
- **Brakes**: A brake acts similarly to a clutch except that one of the members is fixed.[33]

In multi-ratio gearboxes, clutches are vital for smooth transitions between gear ratios. Although specific clutch mechanisms may vary, the concept remains the same across different types of gearboxes, including those used in electric vehicles. It should be noted that not all electric vehicle gearboxes use traditional clutch mechanisms, as many rely on single-speed transmissions that do not require frequent gear shifting. However, for **multi-ratio transmission configurations** (as outlined in Section 2.3.2), clutches still play an important role in maintaining efficient power transfer during gear changes.

2.4.4 Gears

The type of mechanical power transmission is one of the key aspects defining gearbox topology, as noted in Section 2.2, and gears are the primary method used in electric vehicle gearbox topologies, as identified in Section 2.3. Gears are the heart of a gearbox, responsible for transmitting rotary motion and altering torque and speed. Different types of gears are employed depending on the specific needs of the transmission system:

[29] cf.Molotnikov; Molotnikova (Shaft and Axle Supports), 2023, p. 555.
[30] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), 981.
[31] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 746.
[32] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), p. 978.
[33] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 746.

- **Spur Gears**: "*Spur gears* are used to transmit rotary motion between parallel shafts. They are cylindrical, and the teeth are straight and parallel to the axis of rotation."[34] Their straightforward design makes them ideal for simple applications where noise and vibration are not critical concerns.

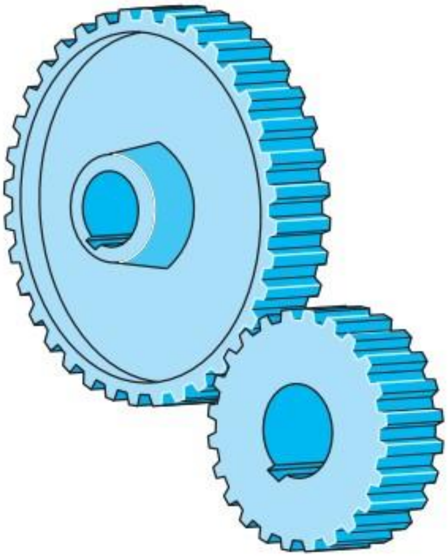

Figure 2.2: Spur gears.[35]

- **Helical Gears**: Helical gearing, in which the teeth are cut at an angle with respect to the axis of rotation, is a later development than spur gearing and has the advantage that the action is smoother and tends to be quieter. In addition, the load transmitted may be somewhat larger, or the life of the gears may be greater for the same loading, than with an equivalent pair of spur gears. Helical gears produce an end thrust along the axis of the shafts in addition to the separating and tangential (driving) loads of spur gears. Where suitable means can be provided to take this thrust, such as thrust collars or ball or tapered-roller bearings, it is no great disadvantage.[36]

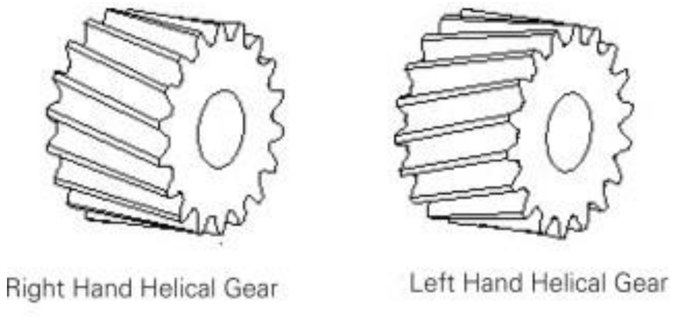

Figure 2.3: Helical gears.[37]

[34] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), 1097.
[35] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design).
[36] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), p. 1162.
[37] cf.Niijjaawan; Niijjaawan (Gears), 2010.

- **Bevel and Hypoid Gears**: Bevel and hypoid gears are suitable for transmitting power between shafts at practically any angle and speed. The load, speed, and special operating conditions must be defined as the first step in designing a gear set for a specific application. Bevel gears, with their conical teeth, and hypoid gears, with their offset axes, provide flexibility in gearbox design.[38]

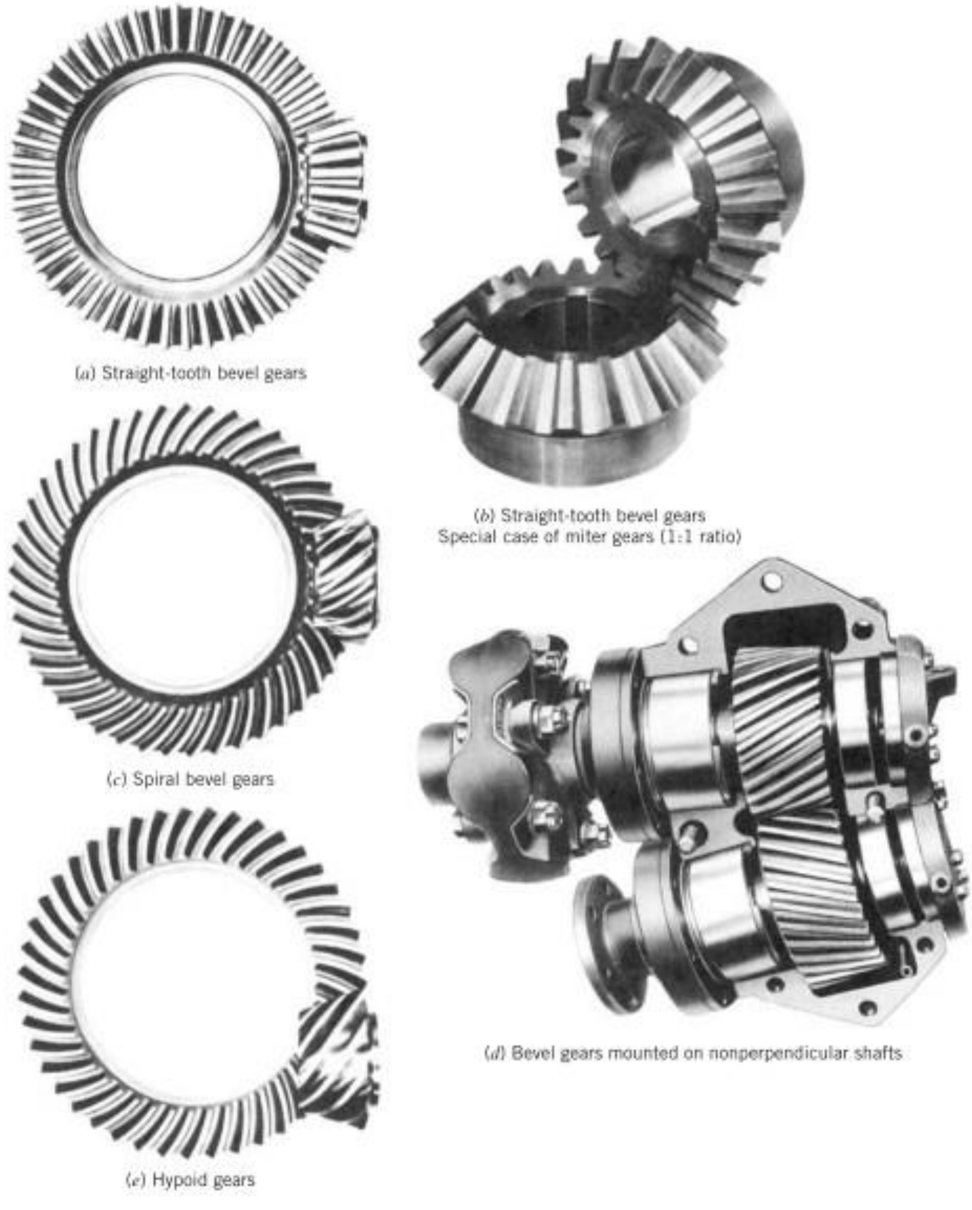

Figure 2.4: Types of bevel gears. (a, *c, d, e,* Courtesy Gleason Machine Division. *b,* Courtesy Horsburgh & Scott.)[39]

- **Planetary Gears**: Planetary gears are highly efficient for high torque transmission through multiple gear engagements. In a typical planetary transmission or epicyclic gear system, the basic form consists of a sun gear, a carrier which carries planetary

[38] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design), p. 1115.
[39] cf.Joseph E. Shigley; Charles R. Mischke (Standard Handbook of Machine Design).

gears, and the ring gear. The sun gear is positioned in the middle of the transmission. The sun, the carrier, and the ring gear are aligned coaxially. The carrier supports the planetary gears, which rotate around and roll over the sun. Typically there are three to five planetary gears. If there are more planetary gears, the load is spread among those gears, so three planetary gears may usually be encountered in lighter transmissions. The planets are surrounded by a ring gear whose internal toothing meshes with the planetary gears. This configuration allows for high reduction ratios while maintaining a compact design.[40]

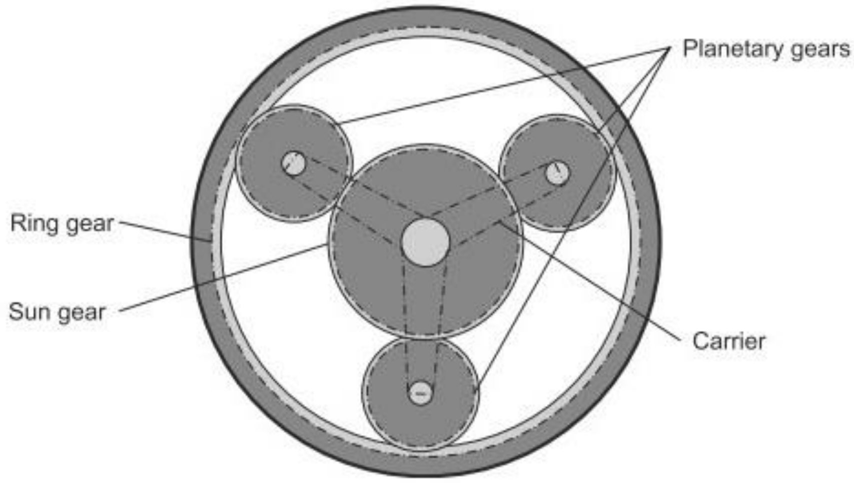

Figure 2.5: The planetary gear set consists of the sun, the ring gear and the carrier with the planetary gears.[41]

2.5 The Key Gearbox Components for Loss Analysis

Among the components discussed previously, certain elements have a more significant impact on the losses occurring within a gearbox. Identifying which components contribute most to power loss is critical in selecting an appropriate loss model for further analysis. According to Niemann and Winter, power losses in a transmission are divided into load-dependent and load-independent losses, primarily originating from gears, bearings, seals, and auxiliary systems. Within those components the following were selected for detailed analysis due to their central roles in power transmission and their influence on loss mechanisms within the gearbox:[42]

- **Gears**: Gears contribute to both load-dependent and load-independent losses. Load-dependent losses arise from friction between the gear teeth as they mesh, while load-independent losses, such as churning losses, occur when gears move through lubricants or oil-air mixtures, creating resistance. These dual sources of power loss make gears the primary component of interest in loss analysis.

[40] cf.Hilgers (Transmissions and drivetrain design), 2023, p. 23.
[41] cf.Hilgers (Transmissions and drivetrain design), 2023.
[42] cf.Shen et al. (General modelling method of power losses in transmission with parameter identification), 2017, p. 118f.

- **Bearings**: Although smaller and seemingly less significant, bearings are crucial to the smooth functioning of the gearbox, reducing friction between moving components and supporting the rotation of shafts and gears. Bearings, like gears, experience both load-dependent and load-independent losses. Load-dependent losses stem from the friction between moving parts, while load-independent losses, including drag losses, result from interactions with lubrication. The role of bearings in minimizing friction-related losses is critical for improving the overall efficiency of the gearbox.

By concentrating on these components—gears, shafts, and bearings—the foundation was laid for an effective analysis of gearbox losses. This focus ensures that the most significant factors affecting the efficiency and performance of the gearbox are thoroughly understood, forming the basis for any subsequent development of tools or models.

2.6 Research Findings on Gearbox Configurations in Electric Commercial Vehicles

The previous sections have established a solid understanding of transmission concepts and the key gearbox components relevant to electric vehicle applications. This background now allows for a focused investigation into the specific gearbox topologies used in electric commercial vehicles and NRMM. By exploring these real-world implementations, the section aims to bridge the gap between theoretical transmission concepts and the practical applications observed in the industry, providing insights that will support further analysis in subsequent sections. The research findings will be presented by vehicle type, detailing the typical gearbox configurations for electric trucks, buses, and NRMM.

2.6.1 Electric Trucks

Electric trucks demonstrate a significant transition from traditional multi-speed transmissions to simpler, more efficient configurations tailored to the unique demands of electric drivetrains. According to Crissey, there has been a shift from traditional 18-speed transmissions to more simplified systems, such as two-speed transmissions. This change is driven by the broader peak torque range of electric motors, reducing the need for complex multi-speed systems[43]. However, the use of multi-speed transmissions, including 2-speed, 3-speed, and 4-speed systems, remains relevant for optimizing energy consumption and performance[44]. Various configurations, such as single transmission, split transmission, and planetary gear train designs, continue to be explored for heavy-duty electric trucks. The research in *Transmissions and drivetrain design*[45] introduces traditional drivetrain layouts alongside innovations such as e-axles, which are noted for their space efficiency, a crucial factor mentioned also by Crissey[46]. Furthermore, Verbruggen emphasizes that selecting the right transmission topology—whether central or distributed—can significantly impact both cost and performance, with multi-speed

[43] cf.Crissey (Inside Electric Truck Transmissions), 2020.
[44] cf.Gözen et al. (Transmission speed and ratio optimization for heavy-duty electric truck), 2022.
[45] cf.Hilgers (Transmissions and drivetrain design), 2023.
[46] cf.Crissey (Inside Electric Truck Transmissions), 2020.

gearboxes playing a key role in reducing the total cost of ownership[47]. A few studies have supported the use of multi-speed transmissions, noting their potential to reduce motor size and energy consumption, with benefits varying depending on the drive cycle and specific configuration[48, 49].

2.6.2 Electric Buses

In the context of electric buses, multispeed gearboxes have been shown to effectively reduce energy consumption and improve overall vehicle performance[50, 51]. For instance, the study by Ritari contrasts two-speed gearboxes with continuously variable transmissions (CVTs), concluding that while two-speed gearboxes can reduce energy consumption, CVTs may actually increase it due to efficiency losses[52]. This finding highlights the importance of choosing the correct transmission type based on specific vehicle requirements. Additionally, the use of dual motor planetary systems underscores a sophisticated transmission strategy for electric buses, offering significant efficiency improvements through advanced control mechanisms[53]. This trend towards complex, multi-component systems in electric buses is reflective of similar developments observed in truck transmissions.

2.6.3 Non-Road Mobile Machinery (NRMM)

For NRMM, the focus is on achieving energy efficiency and simplifying design. The overview provided by Lajunen lays the groundwork for more detailed analyses, such as the one by Brenna, which discusses the advantages of using a fixed-speed ratio transmission in electric farm tractors[54, 55]. This simpler design contrasts with the more complex multi-speed and e-CVT transmissions, which offer energy efficiency benefits similar to those observed in trucks and buses[56, 57]. The research highlights that while simpler designs are often preferred for their reliability and ease of maintenance, more complex configurations like e-CVTs and multi-speed transmissions are also being adopted where additional performance and efficiency gains are necessary.

2.6.4 Common Gearbox Configurations by Vehicle Type

The following are the most prevalent gearbox configurations found across electric trucks, buses, and NRMM, each tailored to the specific needs of these vehicles.

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47 cf.Verbruggen et al. (Electric Powertrain Topology Analysis and Design for Heavy-Duty Trucks), 2020.

48 cf.Verbruggen et al. (Powertrain design optimization for a battery electric heavy-duty truck), 2019.

49 cf.Alexei Morozov, Kieran Humphries, Ting Zou, Tanvir Rahman and Jorge Angeles (Design, Analysis, and Optimization of a Multi-Speed Powertrain for Class-7 Electric Trucks), 2018.

50 cf.Ritari et al. (Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes), 2020.

51 cf.Hasan et al. (Energy Management Strategy in Electric Buses for Public Transport using ECO-driving), 2020.

52 cf.Ritari et al. (Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes), 2020.

53 cf.Wu et al. (Efficiency analysis of planetary coupling drive system with dual motors on electric bus), 2015.

54 cf.Lajunen et al. (Electric and Hybrid Electric Non-Road Mobile Machinery – Present Situation and Future Trends), 2016.

55 cf.Brenna et al. (Feasibility Proposal for Heavy Duty Farm Tractor), 2018 - 2018.

56 cf.Tan et al. (Gear Ratio Optimization of a Multi-Speed Transmission for Electric Dump Truck Operating on the Structure Route), 2018.

57 cf.Rossi et al. (A Hybrid–Electric Driveline for Agricultural Tractors Based on an e-CVT Power-Split Transmission), 2021.

Electric Trucks:

- **Helical Gear Gearboxes**: Commonly integrated into single-speed and two-speed transmissions, offering smooth operation and reduced noise, crucial for commercial vehicles[58, 59].
- **Planetary Gear Gearboxes**: Widely used due to their high torque density and compact design, providing efficient power transmission with multiple gear ratios[60, 61].
- **Bevel Gear Gearboxes**: Essential for changing the direction of force, typically used in drivetrain layouts where orientation change is needed[62].

Electric Buses:

- **Helical Gear Gearboxes**: Utilized in single-speed and two-speed transmissions, particularly in configurations that prioritize noise reduction and efficiency[63].
- **Planetary Gear Gearboxes**: Dual motor planetary systems are prominent for their efficiency and compact design, especially in multi-speed bus transmissions[64].

Non-Road Mobile Machinery (NRMM):

- **Fixed-Speed Gearboxes**: Simplified configurations that provide reliable operation with reduced maintenance needs, likely utilizing helical or bevel gears for their design[65].
- **Planetary Gear Gearboxes**: Similar to trucks and buses, NRMM utilizes planetary systems for their compact and efficient power transmission, particularly in electric tractors[66, 67].

2.6.5 Common Gearbox Configurations in Electric Vehicles

After analyzing the common gearbox topologies across the targeted vehicles (presented in Section 2.6.4), three primary gearbox configurations emerge as dominant across various applications: helical gear, bevel gear, and planetary gearboxes. Additionally, a variant of the planetary gearbox, equipped with dual motors, has gained traction, particularly in hybrid applications. This research suggests that such configurations are also viable for pure electric vehicles. These gearbox designs exhibit a modular nature, allowing them to be repeatedly utilized or integrated into the transmission layouts of electric commercial vehicles. For instance, a transmission may consist of two stages of helical gears, demonstrating the repeated application of

[58] cf.Gözen et al. (Transmission speed and ratio optimization for heavy-duty electric truck), 2022.

[59] cf.Alexei Morozov, Kieran Humphries, Ting Zou, Tanvir Rahman and Jorge Angeles (Design, Analysis, and Optimization of a Multi-Speed Powertrain for Class-7 Electric Trucks), 2018.

[60] cf.Verbruggen et al. (Powertrain design optimization for a battery electric heavy-duty truck), 2019.

[61] cf.Hilgers (Transmissions and drivetrain design), 2023.

[62] cf.Hilgers (Transmissions and drivetrain design), 2023.

[63] cf.Ritari et al. (Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes), 2020.

[64] cf.Wu et al. (Efficiency analysis of planetary coupling drive system with dual motors on electric bus), 2015.

[65] cf.Brenna et al. (Feasibility Proposal for Heavy Duty Farm Tractor), 2018 - 2018.

[66] cf.Tan et al. (Gear Ratio Optimization of a Multi-Speed Transmission for Electric Dump Truck Operating on the Structure Route), 2018.

[67] cf.Rossi et al. (A Hybrid–Electric Driveline for Agricultural Tractors Based on an e-CVT Power-Split Transmission), 2021.

this topology, or a combination of a helical gear stage with a differential employing a bevel gear structure. The versatility and proven effectiveness of these topologies are evident in their widespread adoption across different vehicle types.

- **Helical Gear Gearboxes**: Offering smooth operation and reduced noise, these are ideal for electric vehicles where quiet operation is essential. They are commonly integrated into one-speed transmissions, simplifying the drivetrain, which is crucial for commercial fleet vehicles[68, 69].
- **Bevel Gear Gearboxes**: Essential for changing the direction of force, typically at a 90-degree angle. They handle high torque and power, making them ideal for machinery and vehicles where angular motion transfer is needed[70].
- **Planetary Gear Gearboxes**: Offering high torque density and a compact design, these are suitable for applications that demand robust and compact transmission systems with high stability and efficiency[71, 72, 73].
- **Planetary Gearboxes with Two Motors**: This advanced topology integrates two motors into the planetary gear system, enhancing control and power distribution. It offers improved torque management, redundancy, and reliability, making it ideal for high-performance and precision-demanding applications[74].

In conclusion, the preference for these gearbox topologies is driven by their ability to optimize performance and efficiency across various applications. One-speed helical gear gearboxes provide smooth and efficient operation with low maintenance, bevel gear gearboxes are crucial for changing force direction with high torque, and planetary gear gearboxes offer compact and efficient power distribution. These configurations are not only versatile but also proven in various applications, from trucks and buses to non-road mobile machinery.

2.7 Research and Selection of the Loss Calculation Model

In the preceding sections, a comprehensive examination of gearbox topologies and essential components was conducted to establish a clear understanding of their influence on transmission losses. This analysis not only clarified the key loss mechanisms—particularly load-dependent and load-independent losses—but also provided insight into the specific transmission configurations commonly used in electric commercial vehicles and NRMM. The findings on gearbox topologies and their implementation across vehicle types in Section 2.6 further rein-

[68] cf.Gözen et al. (Transmission speed and ratio optimization for heavy-duty electric truck), 2022.

[69] cf.Alexei Morozov, Kieran Humphries, Ting Zou, Tanvir Rahman and Jorge Angeles (Design, Analysis, and Optimization of a Multi-Speed Powertrain for Class-7 Electric Trucks), 2018.

[70] cf.Hilgers (Transmissions and drivetrain design), 2023.

[71] cf.Hilgers (Transmissions and drivetrain design), 2023.

[72] cf.Verbruggen et al. (Powertrain design optimization for a battery electric heavy-duty truck), 2019.

[73] cf.Ritari et al. (Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes), 2020.

[74] cf.Wu et al. (Efficiency analysis of planetary coupling drive system with dual motors on electric bus), 2015.

forced the need to tailor the loss calculation model to the unique characteristics of these transmissions. With this foundational knowledge, it is now possible to evaluate existing loss models based on their ability to account for the dominant loss factors identified earlier.

Given the importance of maintaining design flexibility in the early stages of development, it was crucial to select a model that balances accuracy with simplicity and is adaptable to situations where detailed input data may not be available. To find the most appropriate model, an extensive review of existing methods and approaches was conducted.

This research was driven by the need to accurately calculate gearbox losses in the context of electric commercial vehicles. While many loss calculation methods could potentially be applied, the specific requirements of the tool being developed necessitated a targeted approach. Initially, the search was broad, focusing on any tool that could facilitate the calculation of gearbox losses at an early design stage.

2.7.1 Criteria for Model Selection

To guide the selection process, four key criteria were established to ensure that the chosen model would align with the goals of the Python tool:

1. **Adaptability to Limited Data**: The model needed to function effectively with basic design parameters, acknowledging that detailed design information might not be available during the early stages of gearbox development.
2. **Computational Efficiency**: The model should facilitate quick iterations, enabling rapid evaluation of different gearbox configurations without requiring extensive computational resources.
3. **Accuracy and Reliability**: Despite the constraints of early-stage design, the model should still provide sufficiently accurate predictions of transmission losses to ensure reliable simulation results.
4. **Minimal Dependence on Experimental Data**: The model should not rely heavily on empirical validation, as such data may not be feasible to obtain during the initial phases of design.

2.7.2 Evaluation of Loss Calculation Models

Along the research, different loss calculation models and approaches were identified, and here some of the findings of the research are presented. These documents present different ways of calculating the losses on a gearbox. All of them will be separately evaluated and later a comparison will be conducted to try to identify which one best fits the objectives and tasks of this work.

1. **Model 1**[75]

[75] cf.Shen et al. (General modelling method of power losses in transmission with parameter identification), 2017.

Overview

This model introduces a comprehensive method for predicting the overall efficiency and power losses in various types of transmissions. The model is a combination of standard industry models and a new joint overall model developed by integrating different component loss models, including gear meshing losses, oil churning losses, and bearing losses.

Methodology[76]

The model calculates gearbox losses by separating them in different categories:

- **Gear Meshing Losses**: Calculated using detailed equations that require specific parameters such as sliding velocity (V_s), friction coefficient (f), and tooth normal force (F_n). The overall sliding power loss is obtained through integration over the path of contact:

$$P_s(x) = |V_s(x)| \times f(x) \times F_n(x) \quad (1)$$

  To obtain the total sliding power loss, this expression is integrated over the contact path from the start point (x_a) to the end point (x_d):

$$P_s = \frac{1}{x_d - x_a} \times \left[2 \times \int_{x_a}^{x_b} P_s(x)d(x) + \int_{x_b}^{x_c} P_s(x)d(x) + 2 \times \int_{x_c}^{x_d} P_s(x)d(x) \right] \quad (2)$$

  This method allows for a precise estimation of losses associated with gear meshing, which are directly related to the gear geometry and frictional properties.

- **Oil Churning Losses**: Calculated using empirical models that account for the interaction of gears with lubricating oil. The losses are influenced by factors such as oil viscosity, gear speed, and immersion depth, and are modeled as:

$$T_{pl} = 1.86 \times 10^{-3} \times \left(\frac{\eta_{oil}}{\eta_0}\right)^{-1.255} \times \left(\frac{R_a}{R_0}\right)^{-1.255} \times C_{wz} \times C_{wa} \times C_M \times C_V \times \eta_{oil} \times v_t \times A_B \quad (3)$$

- **Bearing Losses**: The model also calculates load-dependent and load-independent losses in bearings using empirical formulas provided by manufacturers. These include rolling friction, sliding friction, and lubrication drag torques, reflecting the real-world conditions in which the bearings operate.

Strengths

This model's strength lies in its detailed and systematic approach to calculating gearbox losses. By combining different loss mechanisms into a joint model, it offers a potentially accurate prediction of overall efficiency. The model's use of established industry standards, like ISO 14179, provides a foundation of reliability.

Weaknesses

The complexity of this model and its reliance on detailed input data make it less suitable for early-stage design tools where such data might not be available. The model's requirement for

[76] cf.Shen et al. (General modelling method of power losses in transmission with parameter identification), 2017.

precise information, such as specific gear geometry and lubrication properties, limits its adaptability in scenarios with limited data. Additionally, the model involves complex integrations and empirical coefficients, which can be computationally intensive and difficult to implement in a flexible Python tool.

Suitability

This model, while thorough, is not well-suited for a Python tool intended for early-stage gearbox design. The complexity, data requirements, and computational intensity of the model make it challenging to use in situations where only basic or estimated data is available. Furthermore, the model's reliance on specific detailed parameters reduces its flexibility, which is essential for the Python tool's intended purpose.

2. **Model 2**[77]

Overview

This model proposes a prediction method for gearbox power loss based on dimensionless analysis, incorporating factors such as gear design parameters, lubrication oil properties, and operating conditions. The model was developed to improve the efficiency of gearbox designs by accurately predicting power losses, thereby enabling early design modifications before physical testing. The focus of the model is on helical gears, which is evident from the validation tests conducted on gear pairs with different helical angles.

Methodology[78]

The model employs a dimensionless analysis approach, which is rooted in fluid mechanics principles, including the π theorem and dimensional similarity criteria. The main steps in the methodology are:

- **Dimensionless Analysis**: The model uses the π theorem to express the relationship between physical quantities involved in gearbox power loss. This includes gear design parameters like modulus, helix angle, and tooth height, as well as lubrication factors such as oil viscosity and immersion depth. The power loss is expressed in a dimensionless form:

$$\frac{\Delta P}{\mu h v^2} = f_2\left(\frac{nh}{v}, \frac{\mu h^2 v}{M}, \frac{m}{h}, i, \frac{b}{h}, \beta, \frac{h_t}{h}, \frac{\mu h^5 v}{\rho}\right) \tag{4}$$

  This equation accounts for various influencing factors in a unified model, enabling the prediction of power loss based on a combination of dimensionless groups.

- **Load and No-Load Losses**: The model distinguishes between load-dependent and load-independent losses. The no-load power loss includes gear churning loss, bearing churning loss, and windage loss, while the load power loss includes gear meshing loss and bearing friction loss. The total power loss is then determined as:

$$P_T = P_M + P_S \tag{5}$$

[77] cf.Guo et al. (A Theoretical and Experimental Study on the Power Loss of Gearbox Based on Dimensionless Analysis), 2023.

[78] cf.Guo et al. (A Theoretical and Experimental Study on the Power Loss of Gearbox Based on Dimensionless Analysis), 2023.

where P_T is the total power loss, P_M is the load power loss, and P_S is the no-load power loss.

- **Prediction Model**: The final prediction model for gearbox power loss is derived using multiple linear regression, resulting in a formula that integrates the dimensionless groups with coefficients determined experimentally:

$$\Delta P = 1.7183 \times \mu h v^2 \times \left(\frac{nh}{\nu}\right)^{1.4391} \times \left(\frac{\mu h^2 v}{M}\right)^{-0.3612} \times \left(\frac{m}{h}\right)^{0.1288} \times \left(\frac{z_2}{z_1}\right)^{-0.0965} \times \left(\frac{b}{h}\right)^{0.3663} \times \left(\frac{\beta}{\pi}\right)^{0.1071} \times \left(\frac{h_i}{h}\right)^{0.7983} \times \left(\frac{\mu h^5 v}{\rho}\right)^{-0.0558} \tag{6}$$

This equation encapsulates the influence of gear geometry, lubrication, and operating conditions on the power loss in a gearbox.

Strengths

This model is particularly robust due to its comprehensive consideration of various factors influencing gearbox power loss. By integrating multiple dimensionless groups, the model can predict power losses under a wide range of operating conditions with good accuracy. The use of a dimensionless approach allows for scalability and adaptability to different gearbox designs within the specific context of helical gears. Additionally, the model's predictions were validated against experimental data, showing good agreement across various conditions.

Weaknesses

The model's complexity, due to its reliance on multiple dimensionless groups and experimental coefficients, may pose challenges for implementation in early-stage design tools. Furthermore, the model is primarily validated for helical gears, which raises concerns about its adaptability to other types of gears that are common in electric commercial vehicles, such as bevel gears and planetary gears. The model is not suitable for use with these other gear types, making it less versatile for broader applications in electric commercial vehicle gearboxes. Additionally, the requirement for detailed input data, such as specific gear parameters and lubrication properties, limits its flexibility when only basic or estimated data is available.

Suitability

This model offers a high degree of accuracy and robustness, making it suitable for detailed gearbox design analysis, particularly for helical gears. However, its applicability is limited to helical gears and does not extend to other types of gearboxes, such as those using planetary gears, which are common in electric commercial vehicles. The model's reliance on specific gear types and the need for detailed input data make it less ideal for a Python tool aimed at early-stage gearbox design, where flexibility and simplicity are crucial.

3. **Model 3**[79]

[79] cf.Pelchen C., Schweiger C., Otter M. (Modeling and Simulating the Efficiency of Gearboxes and of Planetary Gearboxes), 2002.

Overview

This model provides a detailed approach to modeling and simulating the efficiency of gearboxes, focusing on the frictional effects present in both standard and planetary gearboxes. The model accounts for various frictional sources, including bearing friction and gear mesh friction, which are critical in determining the overall efficiency and performance of the gearbox. It emphasizes the mathematical modeling of these frictional losses and their impact on gearbox dynamics, with an aim to enable accurate simulations that reflect real-world gearbox behavior under different operating conditions.

Methodology[80]

The methodology behind this model involves a comprehensive mathematical formulation of the frictional losses in gearboxes. The key components of the methodology include:

- **Bearing Friction**: Bearing friction is modeled by considering the torques acting on the shaft in the bearing. The friction torque τ_{bf} is a function of the shaft speed ω, bearing load f_N, temperature T, and lubrication conditions. The relationship is expressed as:

$$\tau_B = \tau_A - \tau_{bf} \tag{7}$$

  where,

$$\tau_{bf} = \begin{cases} \geq 0 & : \omega > 0 \\ \leq 0 & : \omega < 0 \\ 0 & : \omega = 0 \end{cases} \tag{8}$$

  The friction torque depends on whether the shaft is rotating and in which direction, with different frictional characteristics at different speeds.

- **Mesh Friction Calculation**: The friction between gear teeth in contact is another significant contributor to power loss. The model derives the mesh friction efficiency η_{mf1} based on the sliding velocity between the contact points and the gear geometry. The torque equilibrium in the gear mesh is expressed as:

$$\eta_{mf1} = \frac{1 - s_v \mu \frac{d_B}{l_B}}{1 - s_v \mu \frac{d_A}{l_A}} \tag{9}$$

  Here, s_v is a sign factor based on the relative sliding direction, μ is the coefficient of friction, and d_A, l_A, d_B, and l_B are geometric parameters related to the gear teeth. This formulation captures the efficiency of power transmission, considering frictional losses during gear meshing.

- **Planetary Gear Efficiency**: The model also extends to planetary gearboxes, where the efficiency is similarly affected by frictional losses in the bearings and gear meshing. The torque losses in planetary gears are modeled by considering the relationships between the angular velocities and torques of the shafts, using similar principles as those applied to standard gears.

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[80] cf.Pelchen C., Schweiger C., Otter M. (Modeling and Simulating the Efficiency of Gearboxes and of Planetary Gearboxes), 2002.

Strengths

The model's main strength lies in its detailed and accurate representation of frictional losses within gearboxes. By focusing on both bearing friction and gear mesh friction, the model provides a realistic simulation of gearbox efficiency under various operating conditions. The use of well-established mathematical principles ensures that the model can be applied to a wide range of gearbox configurations, including standard and planetary gearboxes, making it versatile for different types of electric commercial vehicles. Additionally, the model's emphasis on simulating real-world effects like stick-slip behavior enhances its practical applicability in dynamic simulations.

Weaknesses

Despite its detailed approach, the model's complexity may pose challenges for early-stage design applications, where simplicity and speed are crucial. The need for specific geometric and frictional parameters, along with the computational intensity of simulating frictional effects, can make the model difficult to implement in situations where only limited data is available. Furthermore, the model's focus on detailed frictional effects might limit its usability in scenarios where a broader, more simplified efficiency estimate is required, potentially reducing its alignment with the goals of developing a versatile and adaptable tool for early-stage gearbox design.

Suitability

This model's detailed and realistic approach to frictional losses makes it highly suitable for in-depth analysis and simulation of gearbox efficiency. However, its complexity and reliance on specific data inputs may limit its applicability in the early stages of gearbox design, where flexibility and the ability to work with incomplete data are essential. While the model offers high accuracy and robustness, it may be better suited for later stages of design or for situations where detailed input data is readily available, rather than for a Python tool intended for rapid, early-stage design iterations.

4. **Model 4**[81]

Overview

This model was developed as part of a study to evaluate and simulate the efficiency and losses in a planetary gearbox designed for industrial applications. The focus of the model is on accurately predicting losses such as sliding, rolling, and churning losses that occur in a planetary gear system. The model is built on established theoretical principles and validated against experimental data to ensure its accuracy.

Methodology[82]

The methodology involves a detailed calculation of various loss mechanisms in the planetary gearbox:

[81] cf.Adam Lundin; Peter Mårdestam (Efficiency Analysis of a Planetary Gearbox), 2010.

[82] cf.Adam Lundin; Peter Mårdestam (Efficiency Analysis of a Planetary Gearbox), 2010.

- **Sliding losses** are calculated by analyzing the interaction between gear teeth during meshing. The sliding power loss is determined using the sliding force $F_s(x)$, derived from the contact normal load, and the sliding velocity $V_s(x)$.

$$P_s(x) = F_s(x) \times V_s(x) \tag{10}$$

- **Rolling losses** arise from the pressure build-up in the lubricant as gears roll against each other. The rolling power loss is calculated by considering the fluid film thickness, contact normal load, and rolling velocity.

$$P_r(x) = C_3 \times F_r \times V_r(x) \tag{11}$$

  In this equation, $P_r(x)$ is the rolling power loss, F_r is the rolling force, $V_r(x)$ is the rolling velocity, and C_3 is a constant that adjusts for specific characteristics of the rolling interaction.

- **Gliding losses** occur when surfaces glide against each other, particularly in vertical orientations. The power loss due to gliding is calculated using the frictional moment M and the rotational speed ω.

$$P_{\text{loss}} = M \times \omega \tag{12}$$

- **Bearing losses** are estimated based on the friction within the needle bearings, considering factors like bearing type, size, and operating conditions.

- **Churning losses**, including drag and pocketing losses, are computed by considering the effects of lubricant viscosity and gear speed, though these are more difficult to quantify precisely.

Strengths

The model effectively captures the various types of losses that occur in planetary gear systems, providing a comprehensive analysis of gearbox efficiency. Its use of established theoretical principles, combined with validation against experimental data, ensures a high level of accuracy in predicting losses. The ability to simulate losses under different conditions makes the model a valuable tool for optimizing gearbox designs.

Weaknesses

One of the main weaknesses of the model is its reliance on detailed input data, including specific gear geometry and lubrication properties. This requirement limits its flexibility, particularly in situations where such data is not readily available. Additionally, the model involves complex calculations, which can be computationally intensive and may require empirical adjustments to match real-world conditions accurately.

Suitability

The model is well-suited for detailed analysis and optimization of planetary gearboxes, particularly in industrial applications where precise data is available. However, its reliance on specific, detailed input data and the complexity of its calculations make it less ideal for early-stage design tools that require flexibility and simplicity. While the model provides a high level of accuracy, it may need adjustments or empirical corrections to be effectively integrated into a Python tool aimed at early-stage gearbox design for electric commercial vehicles.

5. Model 5[83]

Overview

This model is introduced as part of a comprehensive approach to optimizing electric powertrains by integrating an adaptable transmission design method with a generic loss model. The model is designed to account for transmission losses using basic elements that represent different transmission topologies. It employs the Willans line to estimate load-dependent and load-independent losses, making it a versatile tool for early-stage transmission design.

Methodology[84]

The methodology behind this model involves several key steps:

- **Basic Elements:** The transmission is decomposed into basic functional blocks, specifically ratio and shift stages, which can be configured to represent different transmission topologies. The model calculates the transmission losses based on these basic elements, which are tailored to fit various design configurations.
- **Load-Dependent Efficiency:** The model calculates load-dependent efficiency using the Willans line approach, where the input power P_{in} is defined as:

$$P_{\mathrm{in}} = \frac{1}{\eta_{\mathrm{ld}}} P_{\mathrm{out}} + P_{\mathrm{drag}} \tag{13}$$

  Here, η_{ld} represents the load-dependent efficiency, and P_{drag} is the drag power loss. The efficiency of spur gearing $\eta_{\mathrm{ld,sg}}$ is given by:

$$\eta_{\mathrm{ld,sg}} = 1 - \lambda \tag{14}$$

  where λ is the loss factor. For planetary gear sets (PGS), the model accounts for more complex efficiency calculations, considering the power flows within the system.
- **Load-Independent Drag Torque:** Load-independent losses, such as drag torque, are estimated using a data-based approach. The model uses empirical data from existing transmissions to calculate drag torque τ_{drag} as a function of the transmission's design complexity:

$$\tau_{\mathrm{drag}} = a e^{\frac{b}{i}} + c e^{\frac{d}{i}} \tag{15}$$

  where i is the speed ratio, and *a*, *b*, *c*, *d* are coefficients derived from empirical data. This formula enables the estimation of drag torque for different transmission types, including complex multi-speed systems.

Strengths

This model's key strength lies in its adaptability and simplicity, making it ideal for early-stage powertrain development. By using basic elements to define transmission configurations, the model allows for flexible adjustments across different design scenarios. The application of the

[83] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[84] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

Willans line for calculating both load-dependent and load-independent losses ensures rapid and efficient calculations, maintaining computational manageability. Additionally, the integration of empirical data for estimating drag torque enhances its accuracy and flexibility, enabling effective loss estimation without requiring detailed design data. This combination of analytical and data-driven approaches makes the model particularly suitable for integration into a Python tool aimed at early-stage gearbox design for electric commercial vehicles.

Weaknesses
Despite its strengths, the model has limitations. The assumptions made in estimating loss factors, particularly that these factors are constant, may not hold under all operating conditions, potentially leading to inaccuracies in loss predictions. Additionally, while the model is versatile, its reliance on empirical data for certain loss calculations means that its accuracy is contingent on the quality and relevance of the data used.

Suitability
This model is well-suited for integration into a Python tool for early-stage gearbox design due to its adaptability and computational efficiency. Its ability to provide reasonably accurate loss estimates without requiring detailed design data aligns well with the needs of early-stage design, where flexibility and speed are critical. The combination of analytical and empirical approaches allows the model to deliver robust performance across a wide range of transmission designs, making it a valuable asset in the development of electric commercial vehicle powertrains.

2.7.3 Selection of the Loss Calculation Model

After an extensive evaluation of various models, we compared their strengths, weaknesses, and suitability for integration into the Python tool for early-stage gearbox design. The table 2.1 below summarizes the key aspects of each model:

Table 2.1: Comparison of Loss Calculation Models

Model	Strengths	Weaknesses	Suitability for Python Tool
Model 1	• Comprehensive and systematic approach to calculating losses. • High accuracy due to the integration of multiple loss mechanisms.	• Requires detailed input data. • Complex to implement in early-stage design due to computational intensity.	• Not ideal for early-stage design due to complexity. • Best suited for later-stage, detailed analysis.
Model 2	• Robust dimensionless analysis approach. • Validated against experimental data for accuracy.	• Primarily suited for helical gears, less adaptable to other gear types. • Relies on detailed input data, limiting flexibility.	• Highly accurate but limited in scope to specific gear types. • Not flexible enough for early-stage design.

Model 3	• Detailed representation of frictional losses. • Applicable to both standard and planetary gearboxes.	• Requires specific geometric and frictional parameters. • Computationally intensive.	• Highly accurate but complex. • Better suited for detailed simulations rather than early design.
Model 4	• Comprehensive analysis of various loss mechanisms. • High accuracy validated by experimental data.	• Requires detailed input data. • Complex calculations may need empirical adjustments.	• Ideal for detailed analysis in industrial applications. • Less suitable for early-stage, flexible design tools.
Model 5	• Adaptable and simple to implement. • Efficient calculations using the Willans line. • Incorporates empirical data for flexibility.	• Assumes constant loss factors, which may not apply in all conditions. • Relies on empirical data quality.	• Highly suitable for early-stage design due to adaptability and computational efficiency. • Balances accuracy with flexibility, making it ideal for the Python tool.

This summary table 2.1 encapsulates the critical aspects of each model, providing a clear comparison that aids in the selection process.

Given the criteria established earlier in Section 2.7.1, **Model 5** emerges as the most suitable choice for integration into the Python tool. Its adaptability and simplicity make it well-suited for early-stage design, where detailed input data may not yet be available. The use of the Willans line to calculate both load-dependent and load-independent losses ensures that the model remains computationally efficient, a key requirement for the iterative nature of early design phases.

Moreover, the incorporation of empirical data to estimate drag torque enhances its flexibility, allowing it to provide accurate loss estimates across various transmission configurations without the need for exhaustive design details. This makes it particularly valuable for a Python tool intended to support the rapid prototyping and optimization of gearbox designs in electric commercial vehicles.

In contrast, while Models 1 through 4 offer high accuracy and are grounded in rigorous theoretical and experimental foundations, their complexity and dependence on detailed input data makes them less suitable for early-stage design. These models are better aligned with detailed design stages or specific industrial applications where comprehensive data is available, and where computational intensity is less of a concern.

In conclusion, Model 5 provides the optimal balance of accuracy, simplicity, and adaptability, aligning perfectly with the objectives of the Python tool. It will allow for the efficient exploration of a wide design space, enabling the development of innovative gearbox solutions tailored to the specific needs of electric commercial vehicles.

2.8 Research Questions

Through the detailed analysis of gearbox topologies, component interactions, and the influences on loss mechanisms in early-stage gearbox design, this work identified key gaps in existing approaches. Most notably, existing tools and approaches either focus on advanced design stages with complete data or lack the flexibility required for the preliminary exploration of gearbox configurations in electric commercial vehicles. Our review of loss calculation models revealed that while various models exist, few are specifically tailored to the unique requirements of commercial electric vehicles, particularly in terms of their adaptability for early design phases where detailed specifications may not be available.

Furthermore, in reviewing the state of the art, it became clear that existing models do not provide an integrated solution that combines both **loss calculations** and **preliminary sizing** of the gearbox. Gross sizing is a necessary step in ensuring that early-stage designs not only meet performance objectives but also fit within spatial constraints—a critical factor in commercial vehicle applications. Thus, a comprehensive design tool must address both of these areas to be effective for early-stage transmission design.

Based on these findings, the research aims to answer the following questions:

1. **How can a Python tool be developed to effectively calculate loss maps for traction gearboxes in electric commercial vehicles while ensuring flexibility for early-stage design exploration?**
2. **How can this tool support the gross sizing of gearboxes in electric commercial vehicles, allowing for efficient estimation of spatial feasibility during the early design phase?**

These questions are grounded in the recognition that optimizing electric vehicle transmissions requires not only precise loss calculations but also the capacity to ensure that the gearbox configuration is both feasible and scalable. By answering these questions, the thesis contributes a tool that not only supports engineers in evaluating gearbox efficiency but also addresses the physical constraints that often arise in commercial vehicle applications.

3 Architectural Concept and Design of the Tool

3.1 Introduction to Tool Architecture

The development of a Python-based tool for calculating loss maps and performing gross sizing of traction gearboxes in electric commercial vehicles addresses a critical need in the early-stage design process identifies in Chapter 2. As the industry transitions to electric powertrains, particularly for commercial vehicles, the complexity and customization required for each vehicle type necessitate a tool that can provide accurate loss calculations and sizing estimates early in the design phase, even when detailed specifications are not yet available, as stated in Section 2.8.

3.1.1 Identifying the Technical Gap

Our research into gearbox configurations (Section 2.6), key components (Section 2.4 and 2.5), and loss calculation models (Section 2.7) has confirmed and refined our understanding of a critical gap: the absence of a flexible, early-stage design tool specifically tailored for the unique needs of electric commercial vehicles. Designing and optimizing gearboxes for these vehicles involves unique challenges, including varied operational demands and stringent spatial constraints.

Unlike passenger vehicles, which can often rely on more standardized solutions, commercial vehicles require highly customized gearbox configurations. The ability to explore different configurations early in the design process is crucial, yet current methodologies may not provide the necessary flexibility for such early-stage exploration. Furthermore, accurate loss calculations are essential to ensuring the efficiency and reliability of gearbox designs, particularly when detailed design specifications are not yet available. Another critical aspect is gross sizing, which determines whether a proposed gearbox design will fit within the vehicle's spatial constraints—an issue that becomes particularly challenging when working with limited early-stage data.

3.1.2 Requirements for the Tool

The tool being developed must meet several key requirements to address the challenges of early-stage gearbox design for electric commercial vehicles. These requirements are derived from the same principles used to guide the selection of the loss model (Section 2.7.1), ensuring that the tool is adaptable, efficient, accurate, and accessible within the context of limited early-stage data. The criteria applied to the loss model selection directly influence the broader functionality of the tool, guiding its design and architecture.

1. **Flexibility in Handling Various Gearbox Topologies**: The tool must support a wide range of gearbox configurations, including helical, planetary (PGS), bevel, and hypoid gears. The need for flexibility stems from the adaptability criterion, as discussed in Section 2.7.1, where the ability to function with basic input parameters was essential for model selection. Similarly, the tool must accommodate various configurations without

detailed design specifications, as detailed by the criteria of the loss model having minimal dependence on experimental data.

2. **Simplified Input Process**: The tool should be designed to work with simplified input data, allowing users to define basic parameters such as gear ratios, gear types, and key component details without requiring comprehensive design specifications. This approach is vital for enabling early-stage exploration of different design options.
3. **Accurate Loss Estimation Across Multiple Configurations**: The tool's loss calculation capabilities must be robust, enabling accurate predictions of both load-dependent and load-independent losses across the various gearbox topologies identified in our research. Adapting the selected loss model (**Model 5**) to account for the unique characteristics of different gear types is crucial for ensuring reliable performance predictions.
4. **Gross Sizing Capabilities**: The tool must include functionality for gross sizing, allowing engineers to estimate the basic dimensions and space requirements of the gearbox early in the design process. This capability is essential for assessing whether a proposed design will fit within the vehicle's spatial constraints. As well as for the loss model, computational efficiency is required to. By enabling rapid iterations, the gross sizing algorithm ensures that engineers can evaluate whether a proposed design fits within spatial constraints without extensive computational resources.
5. **Modular and Scalable Design**: The architecture of the tool must be modular, allowing for easy updates and scalability. This is particularly important as new gear types or configurations may need to be added in the future. The tool should accommodate these updates without requiring significant changes to its core structure.
6. **User Accessibility**: Despite its technical complexity, the tool must be user-friendly, allowing engineers to input data, run simulations, and interpret results without requiring deep expertise in loss models or programming.

3.2 Conceptual Design of the Tool

Building upon the identified technical gap and the specific requirements outlined in the previous section, the conceptual design of the tool is focused on creating a modular, scalable, and user-friendly architecture. This architecture is strategically developed to address the challenges unique to designing gearboxes for electric commercial vehicles, ensuring flexibility in handling various configurations, precise loss calculations, and effective gross sizing capabilities. The tool's structure is composed of several key components, each responsible for a critical aspect of the design process, ensuring that it meets the needs of engineers during the early stages of gearbox development.

3.2.1 Overview of Key Components

The tool comprises four primary components, each playing a crucial role in the overall design and operation:

- **Input Module**: The Input Module is the starting point of the tool, where users input the necessary data for the design process. This module manages the input through a JSON file, which allows for organized and flexible data handling. The JSON file format is chosen for its simplicity and versatility, enabling users to input various parameters such as gear ratios, gear types, and key component details. The user interacts with the tool through a Python terminal interface, where they can select which configuration from the JSON file to use for calculations. This process ensures that the correct set of parameters is utilized in subsequent calculations.
- **Loss Calculation Module**: This module is responsible for calculating the gearbox losses, divided into two main functions to separately handle load-dependent and load-independent losses. This separation aligns with the theoretical models used, allowing for more precise calculations tailored to the specific characteristics of each loss type. The architecture of this module ensures that updates or refinements to one function can be made independently of the other, maintaining the tool's flexibility.
- **Gross Sizing Algorithm**: The Gross Sizing Algorithm estimates the overall dimensions and spatial requirements of the gearbox. This module is essential for determining whether a proposed design will fit within the vehicle’s spatial constraints. The algorithm is designed to provide quick assessments based on the input data, allowing for efficient exploration of different design scenarios during the early stages.
- **Output Module**: The Output Module consolidates the results from the Loss Calculation and Gross Sizing modules, presenting them in a user-friendly format. It provides detailed loss maps, sizing estimates, and other relevant outputs. The results, including numerical values, are displayed in the Python terminal, while visual outputs, such as heatmaps of losses, are generated using matplotlib and shown in separate windows or saved as files for further analysis.

3.2.2 Architectural Considerations

The architectural design of the tool is guided by several key principles:

- **Modularity**: Each component is designed to operate independently while interacting seamlessly with the others. This modularity ensures that the tool can be easily updated or expanded as new requirements or technologies emerge. For example, the separation of loss calculations into load-dependent and load-independent modules allows for focused improvements in one area without affecting the entire system.
- **Scalability**: The tool’s architecture is scalable, allowing it to accommodate new gearbox types, additional loss models, or expanded sizing algorithms. This scalability is crucial for ensuring the tool remains relevant and useful as the field of electric commercial vehicle design evolves. The use of a flexible input format and modular design allows the tool to grow and adapt to new developments without requiring a complete redesign.
- **Separation of Concerns**: The separation of different types of calculations and processes into distinct modules exemplifies the principle of separation of concerns. By

isolating these calculations, the tool enhances the accuracy and maintainability of the system. This design choice ensures that each aspect of the loss model and sizing algorithm is handled with the appropriate level of detail, improving the reliability of the results.

- **User Accessibility**: User-friendliness was a critical consideration throughout the design process. The architecture is designed to be intuitive, with the JSON input format simplifying data entry and the Output Module providing clear, customizable results. This approach reduces the learning curve, making the tool accessible to engineers with varying levels of expertise.

3.3 Integration and Modularity

The tool’s architecture emphasizes integration and modularity, allowing for efficient collaboration between its components while ensuring that each module can be updated or expanded independently. This section discusses the high-level integration strategy and the modular design that underpins the tool’s flexibility and scalability.

3.3.1 High-Level Integration Strategy

The tool is designed to integrate its components seamlessly, ensuring that data flows smoothly from one module to the next. The Input Module handles the initial data collection and preparation, which is then passed to the Loss Calculation and Gross Sizing modules. These modules process the data independently but share their results with the Output Module, which consolidates the information and presents it to the user in a coherent format.

The integration strategy includes the use of standardized data formats and communication protocols between modules, ensuring that each component can operate independently yet cohesively within the overall system. This strategy also facilitates the use of automated testing frameworks to verify the functionality of each module as they are integrated.

3.3.2 Modularity and Future-Proofing

Modularity is a cornerstone of the tool’s design, ensuring that each component can be updated or replaced without requiring significant changes to the overall system. This design approach is particularly important for future-proofing the tool, allowing for the integration of new gearbox types, updated loss models, or expanded sizing algorithms as the field of electric vehicle design continues to evolve.

This modularity is reflected across the tool's key components, from the flexible input structure to the separation of critical calculations like loss estimation and gearbox sizing. By isolating these components, the tool not only facilitates independent development and testing but also ensures that updates or expansions can be implemented with minimal disruption. For instance, new parameters can be added to the input structure, or new models can be integrated into the calculation modules, without necessitating a complete overhaul of the tool's architecture.

This modular design not only enhances the tool's adaptability but also simplifies maintenance, ensuring that the tool remains a robust and effective solution for the complex demands of electric vehicle gearbox design.

3.4 User-Centered Design

While the primary focus of the tool is on providing accurate and reliable calculations for gearbox loss maps and gross sizing, the design also considers usability within the context of the intended users—engineers and technical professionals working on electric vehicle conversions. However, it is important to acknowledge that the user interface, in this case, was not the highest priority during development, as the software is designed to be integrated into higher-level systems. Therefore, the interface is kept simple, using a JSON file for input data management and a Python terminal interface for executing the calculations.

The decision to use a Python terminal interface and generate visual outputs in separate windows (e.g., through matplotlib) was driven by the need for quick implementation and ease of integration rather than focusing on user experience as a primary concern. This allows the tool to focus more on the back-end functionality of accurate loss map generation and gross sizing without spending resources on building a complex user interface. The expectation is that the tool will eventually be embedded within larger simulation frameworks, where a more advanced user interface might be provided.

The tool uses a JSON file for input, allowing users to define key parameters like gear ratios and load conditions. This format ensures easy adjustments for various gearbox configurations while remaining compatible with higher-level simulation tools. Users interact through a Python terminal, selecting the appropriate configuration for calculations.

The results, including loss maps and gross sizing estimates, are displayed in the terminal or through visual outputs like graphs, generated via matplotlib.

This design prioritizes integration and core functionality, while future iterations may enhance the user interface as the tool evolves within broader design frameworks.

4 Implementation of the Tool

Having established the architectural framework (Chapter 3) and selected the appropriate loss model (Chapter 2), we now move to the implementation phase. This chapter focuses on how the theoretical concepts and design principles are realized in the Python-based tool developed for this project.

The modular architecture outlined in Chapter 3 guides the structure of the tool, ensuring that it effectively handles the diverse configurations typical of electric commercial vehicles. Each module within the tool corresponds directly to the components and processes defined earlier, allowing for accurate loss calculations and gross sizing.

In this chapter, we detail the methodology and implementation strategy, including the structure and processing of input data, the execution of loss and sizing calculations, and the generation of outputs. The implementation described here adheres to the architectural plan, translating conceptual designs into a functional tool that meets the practical requirements of early-stage gearbox design. This implementation is further supported by the detailed theoretical foundations behind the algorithm, which outline the key principles and models governing loss mechanisms and sizing strategies. These theoretical principles ensure that the tool's computational framework accurately reflects the complex behaviors of gearbox components under different operating conditions.

4.1 Implementation of the Input Module

The tool developed for this project is based on a transmission design method that utilizes functional blocks instead of physical components, as defined in **Model 5**[85]. This method allows for the configuration of arbitrary transmissions and is particularly suited to handling the varied configurations typical of electric commercial vehicles.

In order to allow the investigation of arbitrary transmissions, the transmission design method is chosen to be based on functional blocks, instead of physical transmission components such as planetary gear sets (PGS), simple gears (SG), clutches and brakes. These functional blocks, called *basic elements,* are specified by individual *member variables,* which allow to calculate the transmission losses in a subsequent step.[86]

Basic elements*:* Transmissions in single motor electric powertrains can be described as a composition of ratio and shift stages. These are arranged in between the e-drive and the wheels. Any kind of transmission can be described using these two basic elements, allowing to compose different transmission topologies without creating an unnecessary high amount of design candidates. However, only defining the basic elements and their arrangement leads in

[85] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[86] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 7ff.

a transmission model lacking important details. To provide the necessary details to calculate the transmission losses, member variables must be defined for each basic element.[87]

Member variables*:* The ratio stage enables one constant speed ratio between input and output connector and is mainly characterised by this ratio. To calculate the load-dependent efficiency, the realisation of this ratio is required. A speed ratio can be realised either by one SG or one PGSs. If the ratio stage is directly connected to the wheels, a differential must be considered, causing additional drag losses.[88]

In contrast to the ratio stage, the shift stage offers at least two different ratios between in- and output. First, the gear number and their ratios must be defined. Additionally, information about the realisation must be given. Again, either SG or PGS can be employed. Engaging the different gears within a shift stage requires shift elements, which contribute to the load-independent drag losses when opened. To calculate the transmission losses, the number of friction elements and dog clutches opened permanently are required.[89]

These two basic elements can be used to connect e-drive and wheels, which allows to represent any electrical axle system with one EM.[90]

In the named model, several characteristics—such as the type of friction elements and the number of dog clutches—are specified within each shift stage, as shown in Figure 4.1. However, in the tool developed for this project, these characteristics are defined globally within each configuration in the JSON input file. This approach maintains flexibility in modeling various gearbox configurations while simplifying the input format.

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[87] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 7ff.

[88] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 7ff.

[89] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 7ff.

[90] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 7ff.

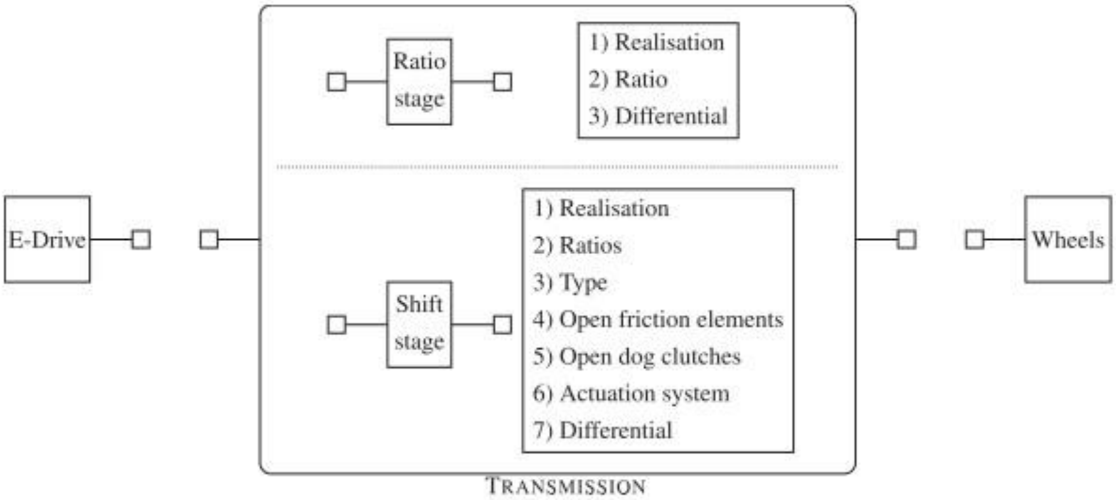

Figure 4.1: Both basic elements and their corresponding member variables in an electric powertrain[91]

As shown in Code sample 4.1 below, they are now defined globally within each configuration block in the JSON file. This means that while these parameters apply to the entire gearbox configuration, they are set outside individual stages, allowing for a cleaner, more streamlined input structure.

```
{
    "material_strength": 400,
    "security_factor": 2.5,
    "configurations": {
        "Validation_document_configuration": {
            "gear_stages": [
                {"type": "ratio", "ratio": 2.4, "realisation": "SG", "operation": "", "gear_type": "helical"},
                {"type": "ratio", "ratio": 2.44, "realisation": "SG", "operation": "", "gear_type": "helical"}
            ],
            "N_open_friction_elements": 0,
            "N_open_dog_clutches": 0,
            "N_open_synchronisation_gaps": 0,
            "N_differential_cages": 1,
            "N_planetary_carriers": 0,
            "N_bearings": 2,
            "N_oil_pumps": 1,
            "number_of_stages": 2,
            "speeds": 1,
            "output_torque": 136.21,
            "RPM_range": 512
        }
    }
```

[91] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

```
23 }
```

Code 4.1: Input Configuration.

This input structure ensures that the necessary parameters are clearly defined and appropriately applied during both the loss and sizing calculations, in line with the intended gearbox design.

Specifically, the following parameters, which were originally managed within the stages in Krüger et al.'s model, are now defined globally for each configuration in the tool:

- N_open_friction_elements
- N_open_dog_clutches
- N_open_synchronisation_gaps
- N_differential_cages
- N_planetary_carriers
- N_bearings
- N_oil_pumps

These parameters are used primarily in the loss calculations to estimate drag losses and to assess the overall efficiency of the gearbox. Although they are defined globally within each configuration, they are still specific to that configuration, allowing the tool to accurately model losses based on the chosen gearbox setup.

On the other hand, stage-specific parameters like **realisation**, **ratio**, and **gear_type** remain within the stages, as these are fundamental to defining the nature and operation of each stage.

The named **gear_type** characteristic was incorporated into each stage in the tool. This addition allows for the integration of various gear types—such as bevel and hypoid gears, alongside the default helical gears—into the tool. This modification was necessary to accommodate the gearbox topologies identified as crucial during the research phase, especially for electric commercial vehicles where different gear types may be required depending on the specific application.

For stages realized with PGS, the gear type is consistently helical, as this is the standard in planetary gear systems. For SG stages, however, the gear type can vary, allowing the tool to model a broader range of gearbox configurations, thereby enhancing its flexibility and applicability.

By managing certain parameters globally while keeping others within the stages, the tool achieves a balance between flexibility and simplicity. This approach allows for consistent modeling across various configurations while maintaining the ability to handle the specific needs of different gearbox setups.

To illustrate how these configurations were originally represented in Krüger et al.’s model, Figure 4.2 below provides examples of one-speed and two-speed SG-based concepts, as well as a one-speed mixed concept. These examples demonstrate how different characteristics—such as gear ratios, realizations, and differentials—are defined within the overall configuration. The figure highlights the original placement and interaction of these characteristics within each concept, providing a clear reference point for understanding how the tool adapts and builds upon these foundational ideas.

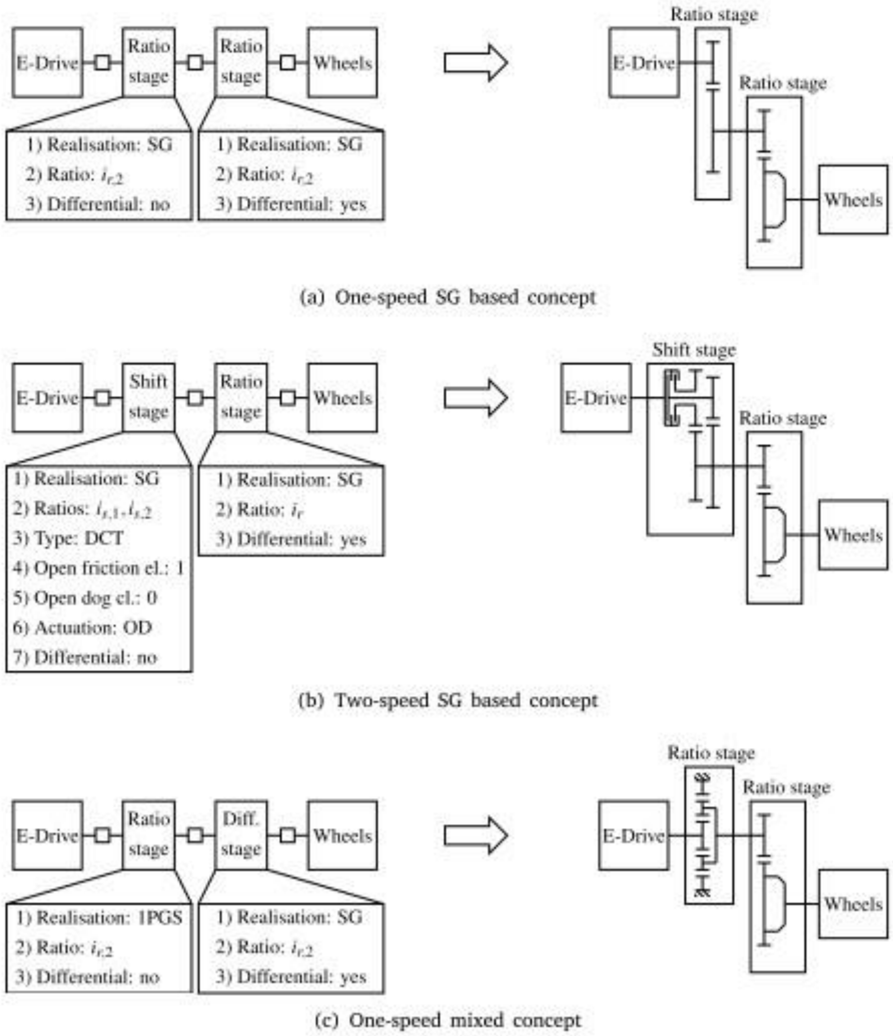

Figure 4.2: Three transmission configurations based on the proposed design method. For each configuration one illustrative physical realisation is shown.[92]

The input structure includes several other characteristics defined outside the stages. Some of these parameters are only necessary for sizing calculations, others for loss calculations, and some for both. Below is a comprehensive explanation of these additional parameters:

- **Material Strength (material_strength)**: This parameter is crucial for sizing calculations, ensuring that the gearbox can handle operational stresses without failure.
- **Security Factor (security_factor)**: A safety margin applied during sizing calculations to account for unexpected loads or material imperfections, ensuring the reliability and safety of the gearbox design.

[92] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

- **RPM Range (RPM_range)**: Specifies the range of rotational speeds that the gearbox must accommodate, influencing both loss and sizing calculations to ensure efficiency across the operating range.
- **Output Torque (output_torque)**: A critical parameter that influences both sizing and loss calculations, determining the size and strength of the gears needed to transmit torque efficiently while also affecting the internal forces and energy losses within the gearbox.
- **Number of Stages (number_of_stages)**: Defines the number of distinct gear stages within the gearbox. It is essential for structuring the gearbox and for ensuring that the correct number of gear stages is considered in both the loss and sizing calculations.
- **Speeds (speeds)**: Indicates the number of speed options available within the gearbox. It is particularly important for configurations that involve shift stages, as it helps to define the range of gear ratios available.

These parameters, in combination, ensure that the input configuration is comprehensive, allowing the program to perform both loss and sizing calculations effectively and tailored to the specific needs of electric commercial vehicle gearbox designs.

To manage these inputs effectively, the tool uses a *GearStage* dataclass that defines the structure of each gear stage. The dataclass is designed to encapsulate all relevant properties needed for both the loss and sizing calculations, ensuring modularity and reusability. Code sample 4.2 presents the full definition of the *GearStage* dataclass:

```
@dataclass
class GearStage:
    """
    Represents a single stage in a gearbox, including details on gear type, dimensions, and operational parameters.
    """
    type: str = None  # Indicates whether the stage is a 'shift' or 'ratio'
    ratio: float = None  # Default to None to handle shift stages properly
    ratios: List[float] = field(default_factory=list)
    realisation: str = None  # Represents the 'realisation' field from JSON (e.g., 'PGS', 'SG')
    operation: str = field(default=None)
    driving_diameter: float = field(default=None)
    driven_diameter: float = field(default=None)
    driving_teeth: int = field(default=None)
    driven_teeth: int = field(default=None)
    sun_diameter: float = field(default=None)
    planet_diameter: float = field(default=None)
    ring_diameter: float = field(default=None)
    sun_teeth: int = field(default=None)
    planet_teeth: int = field(default=None)
    ring_teeth: int = field(default=None)
```

```
    module: float = field(default=None)
    real_operation_ratio: float = field(default=None)
    num_planets: int = field(default=3)
    gear_type: str = None  # Only used for SG gears
```

Code 4.2:GearStage dataclass.

This dataclass creates objects that represent each stage of the gearbox, encapsulating all necessary parameters that describe the stage's behavior and configuration. It allows the tool to handle different types of stages consistently, whether they involve single gear ratios (SG) or more complex planetary gear systems (PGS).

4.2 Implementation of the Loss Calculation Model

4.2.1 Theoretical Background: The Willans Line[93]

The loss model is based upon the assumption that transmission losses can be modelled using the Willans line shown in Figure 4.3. The Willans line is defined as follows.

$$P_{in} = \frac{1}{\eta_{ld}} * P_{out} + P_{drag} \tag{16}$$

In case of an application to transmission losses, the slope of the Willans line is interpreted as the inverse load-dependent efficiency η_{ld}, whereas the intercept with the vertical axis can be interpreted as the load-independent drag losses P_{drag}. Divided by the output speed ω_{out}, Eq. (16) can be transformed into the form of Eq. (17). In this form, the Willans line can be directly applied to each basic element with the load-dependent efficiency η_{ld} and the transmission drag torque t_{drag} of the corresponding basic element.

$$i = \frac{t_{out} + \left(\frac{1 - \eta_{ld}}{\eta_{ld}} * t_{out} + t_{drag}\right)}{t_{in}} \tag{17}$$

Note that the drag torque t_{drag} is imprinted on the output of the basic element. Both load-dependent and load-independent losses depend on the state of operation as well as on the parameters defined in the member variables. In this model, the load-dependent losses are calculated according to analytic equations, while the load-independent losses are approximated using a data-based approach.

[93] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 9.

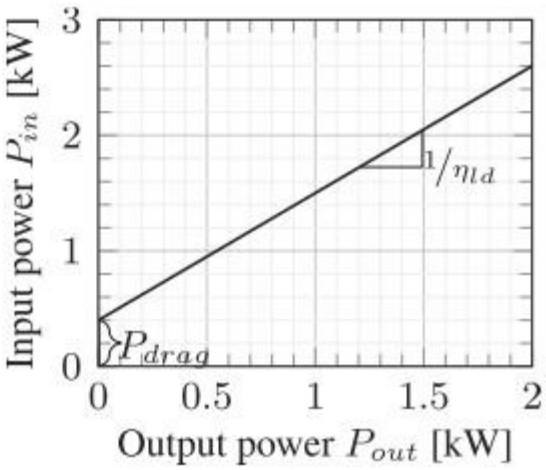

Figure 4.3: Correlation between input and output power according to Willans..[94]

4.2.2 Calculation of Load-Independent Losses

Theoretical Basis: According to the state of the art load-independent losses can be calculated using analytical formulas, as some of the analyzed models stated (Section 2.7) requiring detailed transmission design parameters. The required parameters are not defined by the modelling approach used in this method, this being one of the main reasons this model suites the criteria for each selection. Instead, a data-based approach is chosen using transmission loss data from a transversal seven speed dual-clutch transmission (7DCT), a longitudinal eight-speed automatic transmission (8AT) and a one-speed electric axle system (1ES). Additionally, transmission elements loss data is taken from different research sources and merged with the transmission data.[95]

The load-independent losses are primarily attributed to drag torque, which is calculated using empirical data and a base curve derived from a 7-speed dual-clutch transmission (7DCT). The average drag torque curve for the 7DCT, as described in the model, can be approximated using a two-term exponential function:[96]

$$\tau_{\mathrm{drag,7dct}}(\mathrm{i}) = \mathrm{a} \times e^{\mathrm{b/i}} + \mathrm{c} \times e^{\mathrm{d/i}} \tag{18}$$

The coefficients used in this function are derived from empirical data and fitted to match the performance of the 7DCT and other similar transmissions, such as the 8-speed automatic transmission (8AT). The values of these coefficients, *a*, *b*, *c*, and *d*, are provided in the following table alongside the graph that illustrates the average drag torque as a function of the inverse ratio:

[94] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[95] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 12.

[96] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 12.

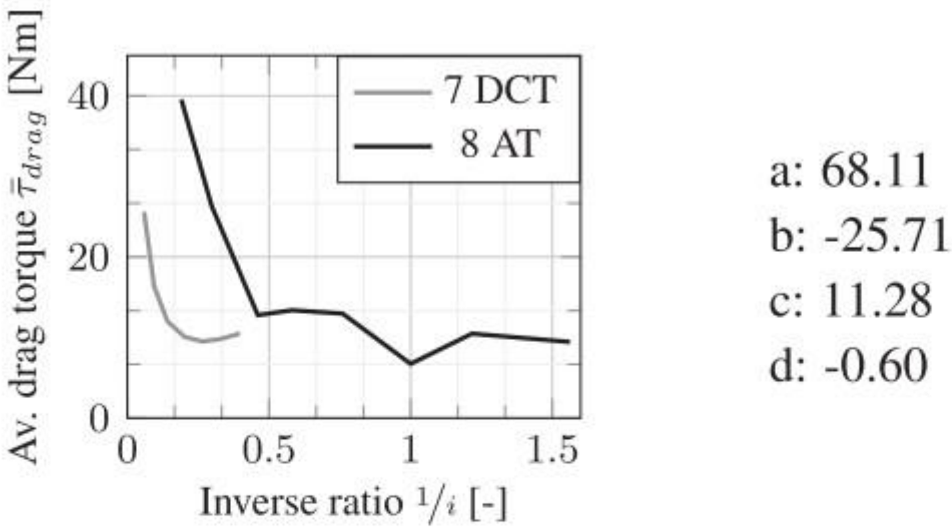

Figure 4.4: Dependency of the averaged drag torque $\tau drag$ and the ratio i.[97]

To accurately model the drag torque for various gearbox configurations, the Python program incorporates the specific drag torque contributions from different components such as open friction elements, dog clutches, synchronization gaps, differential cages, planetary carriers and bearings, and mechanical oil pumps. The following Table 4.1, adapted from Krüger et al., provides the fitted drag torque values for these components:

Table 4.1: Literature values for the averaged drag torque of different transmission components and the fitted value.[98]

Component	Symbol	Value range	Fitted value
Open friction element	$\tau_{drag,cl}$	0.4 – 0.7 Nm	0.5 Nm
Open dog clutch	$\tau_{drag,dc}$	0.08 – 0.12 Nm	0.08 Nm
Open synchronisation gap	$\tau_{drag,sy}$	0.08 – 0.12 Nm	0.08 Nm
Differential cage	$\tau_{drag,d}$	1.4 – 3.7 Nm	1.5 Nm
Planetary carrier and bearings	$\tau_{drag,pgs}$	0.12 – 0.52 Nm	0.37 Nm
Mechanical oil pump	$\tau_{drag,op}$	2.5 Nm	2.5 Nm

Adapting the Base Curve for Different Transmissions

For transmissions with varying complexity, the average drag torque curve must be adapted by adding or subtracting the drag torque contributions of different components. This adaptation involves the following steps:[99]

[97] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[98] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[99] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 12.

1. **Scaling Factor**: Adjust the base drag torque curve based on the number of speeds in the target transmission compared to the base transmission.
$$r_{\text{base}\rightarrow\text{target}} = 1 + 0.12(N_{\text{speeds}} - N_{\text{speeds, base}}) \qquad (19)$$

2. **Component Contributions**: Add or subtract the drag torque contributions of individual components, such as open friction elements, dog clutches, synchronization units, differential, planetary carrier and bearings, and mechanical oil pump.

General Equation

The generalized equation for the average drag torque for an arbitrary transmission can be formulated as:

$$\tau_{drag}(\mathrm{i}) = r_{\text{base}\rightarrow\text{target}} \times \tau_{\text{drag,base}}(\mathrm{i}) + \sum\tau_{\text{drag,add}} - \sum\tau_{\text{drag,remove}} \qquad (20)$$

Note that this equation is only validated for a maximum difference in the number of gears of 6.[100]

In order to know the number of elements we should add and remove, we need to outline the components in the 7-speed dual-clutch transmission (7DCT), this way a comparison with other transmissions will be possible.

Based on the provided information, a 7DCT typically includes the following elements:[101]

1. Non-loaded gears: 7
2. Open friction elements: 1
3. Open dog clutches: 0 (not specified, but typically DCTs do not use dog clutches)
4. Open synchronization gaps: 6
5. Differential: 1
6. Planetary carrier and bearings: 0
7. Mechanical oil pump: 0 (not specified in the document)

Implementation in Python: The Python function **load_independent_losses** implements the calculation of load-independent losses based on the theoretical model described above. The function starts by defining the base configuration for the 7DCT transmission, including the number of open friction elements, dog clutches, synchronization gaps, differentials, planetary carriers, bearings, and mechanical oil pumps. The function then calculates the additional drag torque contributions for the specific gearbox configuration being analyzed:

```
def load_independent_losses(values_input: dict, total_ratio: float) -> Tuple[np.ndarray, np.ndarray]:
    """
    Calculate load-independent losses for the gearbox.

```

[100] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 13.

[101] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 12.

```
    Parameters:
    values_input (dict): A dictionary of input values needed for the calculation.
    total_ratio (float): The total gear ratio for the gearbox.

    Returns:
    Tuple[np.ndarray, np.ndarray]: Two numpy arrays containing total torque losses and total power losses.
    """
    base_speeds = 7
    base_open_friction_elements = 1
    base_open_dog_clutches = 0
    base_open_synchronization_gaps = 6
    base_differentials = 1
    base_planetary_carriers = 0
    base_bearings = 0
    base_mechanical_oil_pumps = 0

    drag_open_friction_elements = (values_input['N_open_friction_elements'] - base_open_friction_elements) * drag_torque_values['Open friction element']
    drag_open_dog_clutches = (values_input['N_open_dog_clutches'] - base_open_dog_clutches) * drag_torque_values['Open dog clutch']
    drag_open_synchronisation_gaps = (values_input['N_open_synchronisation_gaps'] - base_open_synchronization_gaps) * drag_torque_values['Open synchronisation gap']
    drag_differential_cages = (values_input['N_differential_cages'] - base_differentials) * drag_torque_values['Differential cage']
    drag_planetary_carriers = (values_input['N_planetary_carriers'] - base_planetary_carriers) * drag_torque_values['Planetary carrier and bearings']
    drag_bearings = (values_input['N_bearings'] - base_bearings) * drag_torque_values['Planetary carrier and bearings']
    drag_oil_pumps = (values_input['N_oil_pumps'] - base_mechanical_oil_pumps) * drag_torque_values['Mechanical oil pump']

    base_drag_torque = 68.11 * math.exp(-25.71 / total_ratio) + 11.28 * math.exp(-0.6 / total_ratio)
    scaling_factor = 1 + 0.12 * (values_input['speeds'] - base_speeds)
    total_drag_torque = (scaling_factor * base_drag_torque) + drag_open_friction_elements + drag_open_dog_clutches + drag_open_synchronisation_gaps + drag_differential_cages + drag_planetary_carriers + drag_bearings + drag_oil_pumps

    RPM_range = values_input['RPM_range']
    output_torque = int(values_input['output_torque'])
    ang_vel = get_ang_vel(np.arange(RPM_range))
    power_loss = total_drag_torque * ang_vel
    total_power_losses = np.tile(power_loss, (output_torque, 1)) / 1000
```

```
    total_torque_losses = np.tile(total_drag_torque, (output_torque,
RPM_range))

    return total_torque_losses, total_power_losses
```

Code 4.3: load_independent_losses function.

This function calculates the drag torque based on the total ratio of the transmission and scales it according to the number of speeds. The final drag torque is adjusted by adding or subtracting the drag contributions from each component, resulting in the total load-independent losses for the gearbox.

4.2.3 Calculation of Load-Dependent Losses

Theoretical Basis: Load-dependent losses are calculated based on the efficiency of each gear stage, which is determined by whether the stage is of the SG (Simple Gear) or PGS (Planetary Gearset) type.

Load-dependent transmission losses comprise load-dependent meshing and bearing losses, of which the latter amount to 10%. As the bearing losses are comparably low and highly depend on the bearing concept, which is not specified in the design method, they are neglected in this model. Therefore, the load-dependent losses equal the load-dependent meshing losses. All efficiencies mentioned in this subsection refer to load-dependent meshing efficiencies. The load-dependent meshing losses L within a gear-pair can be defined depending on the input power P_{in} and the loss coefficient λ.[102]

$$L = \lambda \times P_{in} \tag{21}$$

Based on this correlation, the efficiency of a spur gearing $\eta_{ld,sg}$ can be written as a function of the loss factor λ.[103]

$$\eta_{ld,sg} = \frac{P_{in} - \lambda \times L}{P_{in}} = 1 - \lambda \tag{21}$$

Generally, the loss factor λ is not constant and depends on various design parameters, such as lubrication conditions and the state of operation. In this study, it is assumed constant. With respect to literature values in, the loss factor for outer toothing is assumed to be $\lambda_0 = 0.01$ and for inner toothing $\lambda_i = 0.005$. For SG based transmissions outer toothing are assumed. Therefore, the efficiency of a SG $\eta_{ld,sg}$ becomes:[104]

$$\eta_{ld,sg} = 1 - \lambda_0 = 0.99 \tag{21}$$

As explained here for SG-based transmissions, the efficiency is assumed to be 0.99 for outer toothing. The efficiency values for another specific gear types, such as spiral bevel gears and

[102] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 10.

[103] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 10.

[104] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 10.

hypoid gears, are derived from Dudley's Handbook[105] and integrated into the model, where typical efficiency ranges are provided. Specific values within these ranges were selected to ensure accurate modeling[106] :

- **Spiral Bevel Gears:** The typical efficiency range is 0.97 to 0.995, with a specific value of 0.98 selected.
- **Hypoid Gears:** The efficiency range is 0.9 to 0.98, with a specific efficiency of 0.94 selected, balancing performance and typical use cases.
- **Helical Gears:** The efficiency of 0.99 assumed in the document is validated by the range provided of 0.97 to 0.995 for external helical gears.

For PGSs, calculating the efficiency is more complex. In this thesis, standard PGSs are considered. The sun gear is denoted with 1, the hollow gear with 2, the carrier with *s* and the planets with *p*."[107]

For PGS stages, the efficiency is calculated using a table from the research paper[108], where the formulas provided there are also derived from the Eq. 21 applied to the virtual power flow of the planetary gear. To use this table, the gear ratio and the virtual power flow (defined by the operation) are required.

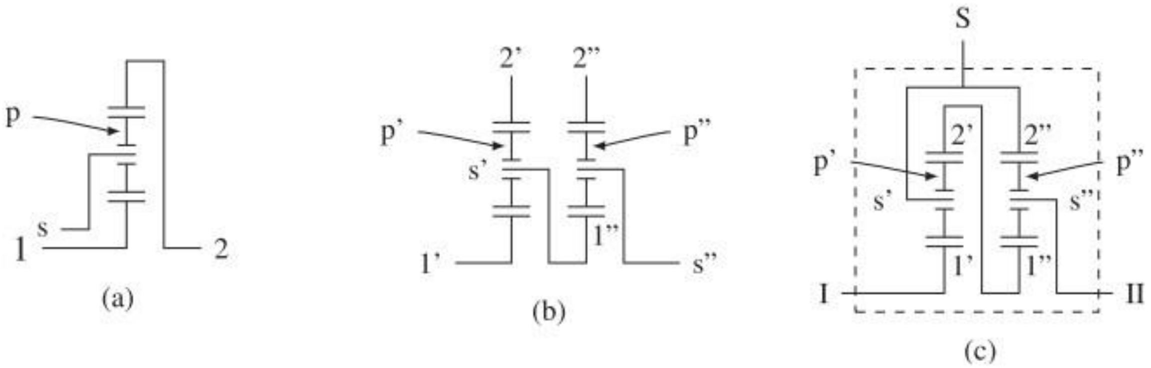

Figure 4.5: Nomenclature of (a) a single PGS, of (b) two PGSs with one couplings and of (c) two PGSs with two couplings. The sun gear is referenced with 1, the carrier with c, the hollow gear with 2 and the planets with p.[109]

The efficiency η_{12} between sun and hollow gear is defined. For the PGS in Figure 4.5 λ_{1p} occurs in an outer toothing, while λ_{p2} occurs in an inner toothing. This results in:[110]

$$\eta_{12} = (1 - \lambda_i)(1 - \lambda_0) = 0.985 \tag{21}$$

[105] cf.Radzevich (Dudley's handbook of practical gear design and manufacture), 2012.

[106] cf.Radzevich (Dudley's handbook of practical gear design and manufacture), 2012, p. 41.

[107] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 10.

[108] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[109] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[110] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 11.

The specific meshing efficiencies for a single PGS in 1DOF operation are summarized in the table below. To determine the efficiency for different operational conditions, both the gear ratio i_{12} and the virtual power flow (defined by the operation) are required. For example, the operation where the input is connected to the sun gear and the output to the carrier (denoted 1→s) varies in efficiency depending on the speed ratio i_{12}. The table illustrates how the efficiency changes based on whether i_{12} is less than 0, between 0 and 1, or greater than 1.

In cases where two elements are connected, the virtual power flow is zero, resulting in no meshing losses and an overall efficiency of 1.

Table 4.2:Meshing efficiency for a single PGS in 1DOF operation.

Operation	$\boldsymbol{i_{12} < 0}$	$\boldsymbol{0 < i_{12} < 1}$	$\boldsymbol{i_{12} > 1}$
$\boldsymbol{1 \rightarrow s}$	$\eta_{ld,pgs} = \frac{i_{12}\eta_{12} - 1}{i_{12} - 1}$	$\eta_{ld,pgs} = \frac{i_{12}/\eta_{12} - 1}{i_{12} - 1}$	$\eta_{ld,pgs} = \frac{i_{12}\eta_{12} - 1}{i_{12} - 1}$
$\boldsymbol{s \rightarrow 1}$	$\eta_{ld,pgs} = \frac{i_{12} - 1}{i_{12}/\eta_{12} - 1}$	$\eta_{ld,pgs} = \frac{i_{12} - 1}{i_{12}\eta_{12} - 1}$	$\eta_{ld,pgs} = \frac{i_{12} - 1}{i_{12}/\eta_{12} - 1}$
$\boldsymbol{2 \rightarrow s}$	$\eta_{ld,pgs} = \frac{i_{12} - \eta_{12}}{i_{12} - 1}$	$\eta_{ld,pgs} = \frac{i_{12} - \eta_{12}}{i_{12} - 1}$	$\eta_{ld,pgs} = \frac{i_{12} - 1/\eta_{12}}{i_{12} - 1}$
$\boldsymbol{s \rightarrow 2}$	$\eta_{ld,pgs} = \frac{i_{12} - 1}{i_{12} - 1/\eta_{12}}$	$\eta_{ld,pgs} = \frac{i_{12} - 1}{i_{12} - 1/\eta_{12}}$	$\eta_{ld,pgs} = \frac{i_{12} - 1}{i_{12} - \eta_{12}}$

This table provides a detailed breakdown of the efficiencies for various PGS operations, helping to predict performance under different configurations. The closer the ratio i_{12} is to one, the higher the overall efficiency. However, with a single PGS, the ratio range is limited to i_{12} between 1.5 and 4. To extend the achievable ratio range from 0.1 to 10, two coupled PGSs are required.[111]

Operation Cases Explained:

1. **Operation 1 → s (Sun Gear to Carrier)**: In this operation, the input power is applied to the sun gear (denoted as 1), and the output is taken from the carrier (denoted as s). This is a common configuration for achieving a reduction in speed while increasing torque. The power flows from the central sun gear to the planets, which in turn drive the carrier. The ring gear (2) is usually held stationary. This operation can be used in scenarios where a high torque output is needed.

2. **Operation s → 1 (Carrier to Sun Gear)**: Here, the input power is applied to the carrier, and the output is taken from the sun gear. This setup can be used to reverse the direction of the gear system or to create an overdrive situation where the output speed (at the sun gear) is higher than the input speed (at the carrier). This operation can be used in specific transmission configurations where such speed increases are desirable.

3. **Operation 2 → s (Ring Gear to Carrier)**: In this case, the input power is applied to the ring gear (denoted as 2), and the output is taken from the carrier. The sun gear is

[111] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 11.

typically held stationary. This configuration also results in a speed reduction with increased torque at the carrier.

4. **Operation s → 2 (Carrier to Ring Gear)**: The input power is applied to the carrier, and the output is taken from the ring gear. This setup is less common but can be used to achieve specific gear ratios or in reverse driving scenarios. The sun gear is usually held stationary.

Implementation in Python: The Python function **calculate_efficiency** implements the calculation of efficiency based on the stage type (SG or PGS) and specific operations for PGS stages. The function in Code sample 4.4 handles different gear types and operations, returning the calculated efficiency.

```python
def calculate_efficiency(stage_type, operation, ratio, efficiency_12, gear_type=None):
    """
    Calculate the efficiency for a given stage.

    Parameters:
    stage_type (str): The type of gear stage (SG or PGS).
    operation (str): The operation mode of the planetary gear stage.
    ratio (float): The gear ratio for the stage.
    efficiency_12 (float): A base efficiency value for the calculation.
    gear_type (str, optional): The gear type, default is None.

    Returns:
    float: The calculated efficiency.
    """
    if stage_type == 'SG':
        if gear_type == "helical" or gear_type is None:  # Default to helical if gear_type is None
            return 0.99
        elif gear_type == "bevel":
            return 0.98
        elif gear_type == "hypoid":
            return 0.94
        else:
            raise ValueError(f"Unsupported gear type: {gear_type}")

    if operation == '1s':
        if ratio < 0:
            return ((ratio * efficiency_12) - 1) / (ratio - 1)
        elif 0 < ratio < 1:
            return ((ratio / efficiency_12) - 1) / (ratio - 1)
        elif ratio > 1:
            return ((ratio * efficiency_12) - 1) / (ratio - 1)
    elif operation == 's1':
        if ratio < 0:
            return (ratio - 1) / ((ratio / efficiency_12) - 1)
        elif 0 < ratio < 1:
```

```
            return (ratio - 1) / ((ratio * efficiency_12) - 1)
        elif ratio > 1:
            return (ratio - 1) / ((ratio / efficiency_12) - 1)
    elif operation == '2s':
        if ratio < 0:
            return (ratio - efficiency_12) / (ratio - 1)
        elif 0 < ratio < 1:
            return (ratio - efficiency_12) / (ratio - 1)
        elif ratio > 1:
            return (ratio - (1 / efficiency_12)) / (ratio - 1)
    elif operation == 's2':
        if ratio < 0:
            return (ratio - 1) / (ratio - (1 / efficiency_12))
        elif 0 < ratio < 1:
            return (ratio - 1) / (ratio - (1 / efficiency_12))
        elif ratio > 1:
            return (ratio - 1) / (ratio - efficiency_12)
    elif operation == '12':
        return efficiency_12
    return 0.99
```

Code 4.4: calculate_efficiency function.

This function is then used within the **load_dependent_losses** function (Code 4.5) to calculate the load-dependent losses for the entire gearbox configuration.

```
def load_dependent_losses(values_input):
    """
    Calculate load-dependent losses for the gearbox.

    Parameters:
    values_input (dict): A dictionary containing input values needed for the calculation.

    Returns:
    Tuple[np.ndarray, np.ndarray]: Two numpy arrays containing total torque losses and total power losses.
    """
    efficiency_12 = 0.985
    RPM_range = values_input['RPM_range']
    output_torque = int(values_input['output_torque'])
    total_torque_losses = np.zeros((output_torque, RPM_range), dtype=np.float64)
    total_power_losses = np.zeros((output_torque, RPM_range), dtype=np.float64)

    torques = np.arange(1, output_torque)
    rpms = np.arange(1, RPM_range)
    ang_vel_stages = get_ang_vel(rpms[:, np.newaxis])
    efficiencies = []

    for properties in values_input['gear_stages']:
```

```
        if properties.realisation == 'PGS':
            print(f"Using real operation ratio for PGS stage: {properties.real_operation_ratio}")
        ratio = properties.real_operation_ratio if properties.realisation == 'PGS' else properties.ratio
        stage_type = properties.realisation
        operation = properties.operation
        efficiency = calculate_efficiency(stage_type, operation, ratio, efficiency_12, properties.gear_type)
        efficiencies.append(efficiency)

    for torque in torques:
        output_power = torque * ang_vel_stages
        tot_power_loss = np.zeros_like(rpms, dtype=np.float64)
        tot_torque_loss = np.zeros_like(rpms, dtype=np.float64)
        output_torque_stage = torque

        for properties, efficiency in zip(reversed(values_input['gear_stages']), reversed(efficiencies)):
            ratio = properties.real_operation_ratio if properties.realisation == 'PGS' else properties.ratio
            input_power = output_power / efficiency
            input_torque = output_torque_stage / (ratio * efficiency)
            power_loss = input_power * (1 - efficiency)
            torque_loss = input_torque * (1 - efficiency) * ratio

            output_power = input_power
            output_torque_stage = input_torque
            tot_power_loss += power_loss.flatten()
            tot_torque_loss += torque_loss.flatten()

        total_torque_losses[torque, 1:] = tot_torque_loss
        total_power_losses[torque, 1:] = tot_power_loss / 1000

    return total_torque_losses, total_power_losses
```

Code 4.5: load_dependent_losses function.

This function calculates the load-dependent losses across the entire gearbox configuration by processing each torque and RPM combination. It iterates through the torque levels and calculates the corresponding output power, then iteratively works backward through the gearbox stages, adjusting the power and torque losses at each step. This reverse computation ensures that the effects of losses are accurately propagated through all stages, from the output back to the input.

The function considers the efficiency of each gear stage, as calculated by the **calculate_efficiency** function, and uses this to determine the input power required at each stage, given the output power. The losses at each stage are summed to provide the total load-dependent losses across the entire gearbox.

This detailed approach provides a comprehensive view of how load-dependent losses affect the gearbox, allowing for precise optimization of its design to minimize these losses under different operating conditions.

4.3 Implementation of the Gross Sizing Algorithm

The gross sizing algorithm is designed to provide a quick and practical estimation of the gearbox dimensions to determine whether a proposed configuration is viable within the given space constraints. The process involves a series of calculations aimed at ensuring that the gears can handle the expected loads without failure, focusing on the bending stress of gear teeth as a key criterion.

Although the sizing algorithm effectively handles helical and planetary gears, it is important to note that the current implementation does not specifically address the sizing of bevel and hypoid gears in the simple gear stages. Instead, the algorithm performs sizing calculations as if all gears in these stages were helical gears, regardless of their actual type. This approach, while not fully accurate for bevel and hypoid gears, still provides valuable insights. If the proposed configuration is feasible when sized under the assumption of helical gears, it suggests that the design is likely robust. Conversely, if the sizing indicates that the design is not viable, this outcome still serves as a useful indicator, prompting further refinement or reconsideration of the gear stage in question.

Moreover, by successfully sizing the other stages of the gearbox, the program ensures that the overall configuration remains within viable limits, even if adjustments are later needed for specific stages involving bevel or hypoid gears. This approach allows the program to contribute meaningfully to the design process, even when exact sizing for all gear types is not implemented. Future improvements could incorporate specific calculations for bevel and hypoid gears, enhancing the precision of the sizing process. Until such improvements are made, the existing approach offers valuable insights and ensures that the gearbox configuration is as optimal as possible within the current scope of the algorithm.

4.3.1 Input parameters

In the development of the gearbox sizing algorithm, the selection of input parameters was guided by established engineering principles and practical considerations. These parameters form the foundation of the sizing process, ensuring that the gearbox can handle the required loads and operate reliably under various conditions.

The preliminary design of a gearbox typically begins with a broad consideration of several key factors, including the type and power of the prime mover, the overall reduction ratio required, and the specific application for which the gearbox is being designed. These factors help to define the basic size and structure of the gearbox. As we progressed with the development of the sizing algorithm, it became clear that a focused set of input parameters was necessary to drive the calculations effectively.[112]

[112] cf.Zdziennicki; Maciejczyk (DESIGN BASIC OF INDUSTRIAL GEAR BOXES), 2011, p. 8.

Through a combination of theoretical understanding and practical refinement, the following key input parameters were identified as crucial for the sizing process. These parameters are the backbone of the algorithm, ensuring that the gearbox is not only designed to meet its operational requirements but also does so with a sufficient margin of safety.

- **Material Strength (material_strength)**: This defines the maximum allowable stress that the material used for the gears can withstand. It is essential for ensuring the gears do not fail under load.
- **Security Factor (security_factor)**: A factor of safety applied to the material strength to account for uncertainties in the design, such as material imperfections or unexpected load increases. By incorporating a security factor, the algorithm ensures that the gears are not only designed to handle the expected loads but also have a margin of safety to accommodate unforeseen conditions. This conservative approach is standard practice in engineering to enhance the reliability and longevity of the gearbox.
- **Output Torque (output_torque)**: The output torque represents the maximum torque that the gearbox must deliver to the output shaft. This parameter is central to the sizing process because it defines the load that the gearbox must transmit. Starting from the output torque, the algorithm calculates the forces acting on each gear stage, ensuring that each component is appropriately sized to handle the torque without excessive stress. The output torque is a critical input that drives the entire sizing process, determining the dimensions and strength of the gears.
- **Gear Stages (gear_stages)**: The gear_stages parameter outlines the sequence of stages in the gearbox. Each stage is characterized by:
    - **Type**: This defines whether the stage is a *shift* stage or a *ratio* stage.
    - **Realisation**: This specifies the type of gear mechanism used in the stage, such as *SG* (Simple Gear) or *PGS* (Planetary Gear Set).
    - **Ratios**: For shift stages, a list of possible gear ratios.
    - **Ratio**: For ratio stages, the specific gear ratio used in that stage.
    - **Operation**: Specific to planetary gears, defining how the gear set operates (e.g., "s1")
    - **Gear Type**: Defines the type of simple gear used in SG stages (e.g., helical, bevel).

  The algorithm processes each gear stage sequentially, adjusting torque and calculating the necessary gear dimensions to ensure that the gearbox meets its performance requirements. This structured approach allows the gearbox to handle varying loads, speeds, and operational conditions, ensuring reliability and efficiency.

4.3.2 Theoretical Basis of the Algorithm

In the early stages of gearbox design, one of the key objectives is to ensure that the proposed configuration is viable within the given space constraints. This gross sizing is crucial for determining whether the gearbox can physically fit within the designated space while also being capable of transmitting the required torque. While a full gearbox design involves many detailed calculations and considerations, the gross sizing process aims to provide a preliminary estimation of the gearbox dimensions to assess its overall feasibility.

To achieve this, the sizing process in this thesis is based on the Lewis equation, a fundamental tool in gear design that assesses the bending stress on gear teeth. We focus on the bending stress because it is one of the most critical aspects of gear durability and performance. By concentrating on this crucial factor, we simplify the sizing process without compromising the ability to ensure that the gears can withstand the operational forces.

The Lewis equation, introduced by Wilfred Lewis in 1893, is used to estimate the bending stress (σ) on a gear tooth, a critical factor in determining whether the gear can handle the applied loads without failure.[113]

$$\sigma_b = \frac{F_t}{b * m * Y} \tag{22}$$

Where:

- F_t is the tangential force on the tooth, derived from the torque that needs to be transmitted.
- b is the face width of the gear, which influences how the load is distributed across the tooth.
- m is the module of the gear, a measure of the gear's size.
- Y is the Lewis form factor, which accounts for the shape and profile of the gear tooth.

The Lewis form factor Y is selected based on the number of teeth (z) and the pressure angle (ϕ) of the gear, and it serves as a constant in the bending stress equation to account for the tooth geometry.

For the gross sizing process to be effective, the calculated bending stress must not exceed the allowable stress for the gear material, adjusted by a safety factor SF to account for uncertainties. This ensures that the gear design is robust enough to handle the expected loads during operation:

$$\sigma \leq \frac{\sigma_{material}}{SF} \tag{23}$$

By focusing on the bending stress, as calculated by the Lewis equation, the gross sizing algorithm provides a straightforward method for estimating the dimensions of the gearbox components. This estimation is crucial for checking whether the proposed gearbox configuration fits within the space constraints and can handle the required torque. While this approach focuses

[113] cf.Mohanraj et al. (Theoretical and Numerical Analysis of Bending Stress on Spur Gears), 2023, p. 523.

on a single aspect of gear design, it is chosen because of its importance, allowing for a simpler and more efficient preliminary sizing process. This process forms an essential part of the early-stage design, allowing for adjustments and refinements before moving on to more detailed design and optimization stages.

4.3.3 Gear Sizing Process

The gear sizing process described in this section builds directly upon the theoretical framework established in Section 4.3.2, particularly the use of the Lewis equation for the bending stress calculations. The algorithm presented here is an original contribution that iteratively applies these principles to determine the optimal gear dimensions. Starting from initial assumptions for key parameters, such as the module size and face width, the algorithm adjusts these values through multiple iterations until the calculated bending stress complies with the allowable limits. This approach allows for a practical and flexible gear sizing method that ensures the gears can withstand operational loads without failure. The choices of initial parameters and the iterative refinement process are based on established gear design principles, but the implementation itself is a unique extension of the theoretical background.

The gross sizing process begins with defining the Input parameters, as explained in Section 4.3.1. The algorithm then proceeds through the following steps:

1. **Initial Parameter Estimation**:

The algorithm starts with initial assumptions for the module size and face width for each stage. These parameters are crucial as they directly affect the gear dimensions and, consequently, the gearbox size.

Module(m): (derived from pitch diameter formula[114] by applying the relationship between module and pitch diameter)

$$m_n = \frac{d}{z} * \cos\beta \tag{24}$$

Where m_n is the normal module, d the pitch diameter, z the number of teeth and β the helix angle (as we will be working with helical gears).

For the estimation of the initial normal module to be made, some values have to be assumed:

Helix Angle (β): For helical gears, a typical helix angle of 20 degrees is assumed.[115]

Number of Teeth (z_initial): The initial number of teeth is a critical parameter in gear design as it directly influences the strength and durability of the gear. For the preliminary sizing of gears, particularly in the last stage of a gearbox where torque is highest, a well-justified starting point is essential. In order to avoid Undercutting for gears with a 20-degree

[114] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 679.
[115] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 678.

pressure angle, a minimum of 18 teeth is generally recommended. Therefore, a value of 25 teeth is selected as provides a safe margin, ensuring robustness under high loads.[116]

Pitch Diameter (pitch_d_initial): The pitch diameter directly affects the gear's size and load-carrying capacity. In high-torque applications, such as in electric commercial vehicles, selecting an appropriate initial pitch diameter is essential. However, it's important to note that this initial estimation is somewhat arbitrary and will be refined through the iterative design process. For that reason, an initial pitch diameter of 150 mm is chosen as a conservative starting point.

Face width (b): The face width is another important parameter, as it influences the load distribution across the gear teeth and ultimately the gear's ability to transmit torque. In this sizing algorithm, the face width *b* is initially estimated to be 10 times the module value in millimeters.

2. Estimation of gear sizes

After defining the size of the pinion for a simple gear, or the size of the sun gear for a planetary gear, based on the initial assumptions, the next step is to estimate the dimensions of the remaining gears in the stage. For a simple gear stage, this calculation is straightforward: it involves multiplying the number of teeth on the pinion by the gear ratio. In contrast, for a planetary gear stage, the gear ratio must be calculated first, as the input provided to the program always represents the ratio between the sun gear and the ring gear.

The following content presents the derivation of gear ratio and torque formulas for planetary gear stages, which vary depending on the operational mode of the gearset. These formulas are derived from the fundamental relationship outlined in Eq. 25, as a comprehensive reference for all specific ratios across operations was not available. Thus, the formulas have been systematically deduced from the relationship hereunder to suit the requirements of the tool's implementation.

$$\omega_1 \times R_1 = \omega_2 \times R_2 + \omega_s \times (R_1 + R_2) \tag{25}$$[117]

Where *s* states for the carrier, *1* for the sun gear and *2* for the ring gear.

For the specific operations, the following derivations are presented:

Sun Input, Carrier Output (Ring Fixed) - Operation "1s"

When the ring gear is fixed ($\omega_2 = 0$):

$$\omega_1 \times R_1 = \omega_s \times (R_1 + R_2) \tag{26}$$

Solving for $\frac{\omega_1}{\omega_s}$:

$$\frac{\omega_1}{\omega_s} = 1 + \frac{R_2}{R_1} \tag{27}$$

[116] cf.Budynas, R. G., & Nisbett, J. K. (Mechanical Engineering Design), 2011, p. 687.
[117] cf.Lynwander (Gear Drive Systems: Design and Application), p. 310.

Considering the number of teeth, we get:

$$Gear\ Ratio = 1 + \frac{Z_2}{Z_1} \tag{28}$$

The torque on the sun gear is the input torque, and the torque on the carrier (output) is:

$$T_s = T_1 \times (1 + \frac{Z_2}{Z_1}) \tag{29}$$

Since the ring gear is fixed:

$$T_2 = 0 \tag{30}$$

Carrier Input, Sun Output (Ring Fixed) - Operation "s1"

When the carrier is the input and the sun gear is the output with the ring gear fixed:

$$\omega_1 \times R_1 = \omega_s \times (R_1 + R_2) \tag{31}$$

Solving for $\frac{\omega_s}{\omega_1}$:

$$\frac{\omega_s}{\omega_1} = \frac{1}{1 + \frac{R_2}{R_1}} \tag{32}$$

The gear ratio in terms of speed is:

$$Gear\ Ratio = \frac{1}{1 + \frac{Z_2}{Z_1}} \tag{33}$$

The torque on the carrier is the input torque, and the torque on the sun gear (output) is:

$$T_1 = T_s \times \frac{1}{1 + \frac{Z_2}{Z_1}} \tag{34}$$

Since the ring gear is fixed:

$$T_2 = 0 \tag{35}$$

Ring Input, Carrier Output (Sun Fixed) - Operation "2s"

When the sun gear is fixed and the ring gear is the input, the carrier becomes the output:

$$\omega_2 \times R_2 = -\,\omega_s \times (R_1 + R_2) \tag{36}$$

Solving for $\frac{\omega_2}{\omega_s}$:

$$\frac{\omega_2}{\omega_s} = -(1 + \frac{R_1}{R_2}) \tag{37}$$

Considering the negative sign due to the fixed sun gear:

$$Gear\ Ratio = -(1 + \frac{Z_1}{Z_2}) \tag{38}$$

The torque on the ring gear is the input torque, and the torque on the carrier (output) is:

$$T_s = T_2 \times \left(-1 - \frac{Z_1}{Z_2}\right) \tag{39}$$

Since the sun gear is fixed:

$$T_1 = 0 \tag{40}$$

Carrier Input, Ring Output (Sun Fixed) - Operation "s2"

When the carrier is the input and the ring gear is the output with the sun gear fixed:

$$\omega_2 \times R_2 = -\omega_s \times (R_1 + R_2) \tag{41}$$

Solving for $\frac{\omega_s}{\omega_2}$:

$$\frac{\omega_s}{\omega_2} = -\frac{1}{1 + \frac{R_1}{R_2}} \tag{42}$$

The gear ratio is:

$$Gear\ Ratio = -\frac{1}{1 + \frac{Z_1}{Z_2}} \tag{43}$$

The torque on the carrier is the input torque, and the torque on the ring gear (output) is:

$$T_s = T_2 \times \frac{-1}{1 + \frac{Z_1}{Z_2}} \tag{44}$$

Since the sun gear is fixed:

$$T_1 = 0 \tag{45}$$

Carrier Fixed, Sun Input, Ring Output - Operation "12"

When the carrier is fixed, the speed relationship simplifies to:

$$\omega_1 \times R_1 = \omega_2 \times R_2 \tag{46}$$

Solving for $\frac{\omega_1}{\omega_2}$:

$$\frac{\omega_1}{\omega_2} = \frac{R_2}{R_1} \tag{47}$$

Considering the number of teeth:

$$Gear\ Ratio = \frac{Z_2}{Z_1} \tag{48}$$

The torque on the sun gear is the input torque, and the torque on the ring gear (output) is:

$$T_2 = T_1 \times \frac{Z_2}{Z_1} \tag{49}$$

Since the carrier is fixed:

$$T_s = 0 \tag{50}$$

3. Calculation of Forces and Stresses:

Tangential Force: For each gear stage, the tangential force F_t is calculated based on the torque transmitted through the gear.

$$F_t = \frac{T_{gear}}{r_{pitch} \times \cos\beta} \tag{51}$$ [118]

Where T_{gear} is the torque on the gear (pinion, sun, ring, or carrier) and r_{pitch} is the pitch radius of the gear. Therefore, when the gear stage realization is PGS, the torque on each of the gears is first calculated based on the specific operational mode of the planetary gearset.

Once the torque for each gear is determined, the tangential force F_t on the gear teeth is calculated using the formula above. This force is crucial as it directly impacts the bending stress on the gear teeth, which is a key factor in ensuring the gears are capable of withstanding the operational loads without failure.

Bending Stress: Using the tangential force and initial gear dimensions, the algorithm calculates the bending stress on each gear tooth using the Lewis equation, Eq. (22) adapted to helical gears:

$$\sigma_b = \frac{F_t}{b' * m * Y} \tag{52}$$

Where the effective face width (b')[119] :

$$b' = \frac{b}{cos\,\beta} \tag{53}$$

The Lewis Form Factor Y varies with the number of teeth. For a 20-degree pressure angle and full-depth teeth, Y ranges from approximately 0.245 for 12 teeth to 0.485 for a rack. For 25 teeth, which is our starting point, the corresponding Y value is approximately 0.337.[120] However, a simplified average value of Y = 0.35 is often used in preliminary designs to streamline calculations.

4. Iteration for Stress Compliance:

- **Stress Check**: The algorithm compares the calculated bending stress against the allowable stress. If the stress exceeds the allowable limit, it indicates that the gear is not sufficiently strong.

---

[118] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 682.
[119] cf.Juvinall; Marshek (Fundamentals of machine component design), 2012, p. 679.
[120] cf.Budynas, R. G., & Nisbett, J. K. (Mechanical Engineering Design), 2011, p. 738.

- **Adjustment of Parameters**: To reduce the stress, the algorithm increases the module size and adjusts the face width accordingly. These adjustments are necessary to ensure that the gears can handle the loads without failure.
- **Recalculation**: After adjusting the parameters, the algorithm recalculates the forces and stresses. This process repeats iteratively until the calculated stress is within the allowable limits.

5. **Finalization of Gear Dimensions**:

   Once the algorithm achieves a design where the bending stress is within the acceptable range, it finalizes the gear dimensions. These dimensions represent the gross size of the gears in the gearbox.

This comprehensive process allows the algorithm to produce a preliminary gearbox design that meets the basic requirements for space and load-handling capacity. While it does not fully optimize the gearbox for all possible conditions, it provides a solid foundation for early-stage design and feasibility assessment.

4.3.4 Implementation in Python

The implementation of the gross sizing algorithm in Python follows a structured approach that reflects the theoretical foundations outlined in the previous sections. The algorithm processes the input parameters, performs the necessary calculations for each gear stage, and iterates to ensure that the final design complies with the required constraints. Below is a breakdown of how the key functions are structured, starting with the main function and delving into the supporting functions following the logical flow of the program.

Main Function: size_multistage_gearbox

The main function that orchestrates the gearbox sizing process is size_multistage_gearbox (Code 4.6). It handles multiple gear stages, performs checks for the correctness of the ratios, and processes each stage iteratively. For each stage, the function calls size_gearbox_stage to compute gear dimensions and stresses.

The function iterates over each gear stage, starting with the output torque as an input parameter. Depending on the type of gear—simple (SG) or planetary (PGS)—the torque is updated accordingly for each subsequent stage. The function also checks for the smallest shift ratio to track the most demanding stage and calls update_max_sizes to record the largest gear sizes encountered in the entire process.

```python
def size_multistage_gearbox(output_torque: float, gear_stages: List[GearStage], material_strength: float, security_factor: float, smallest_shift_ratio: float) -> List[Dict[str, float]]:
    """
    Determine the parameters for each stage of a multistage gearbox.

    Parameters:
    output_torque (float): The output torque for the gearbox.
```

```
    gear_stages (List[GearStage]): A list of GearStage objects representing the stages.
    material_strength (float): The material strength used in stress calculations.
    security_factor (float): The safety factor applied in stress calculations.
    smallest_shift_ratio (float): The smallest shift ratio in the gearbox.

    Returns:
    List[Dict[str, float]]: A list of dictionaries representing the calculated parameters for each stage.
    """
    stages = len(gear_stages)
    T_current = output_torque
    results = []

    for stage in reversed(range(stages)):
        gear_stage = gear_stages[stage]

        # Ensure the ratio is properly set
        if gear_stage.type == "shift":  # Check if it's a shift stage
            if not gear_stage.ratios:
                raise ValueError(f"Shift stage '{gear_stage}' is missing 'ratios'. Please provide valid ratios in the configuration.")
        elif gear_stage.ratio is None:
            raise ValueError(f"Ratio for stage of type '{gear_stage.type}' is not set. Please check the configuration.")

        result = size_gearbox_stage(T_current, gear_stage, material_strength, security_factor, stage + 1)
        results.append(result)

        # Update T_current for the next stage
        if gear_stage.realisation == 'SG' or (gear_stage.realisation == 'PGS' and gear_stage.operation in ['12']):
            T_current = T_current / gear_stage.ratio
        elif gear_stage.realisation == 'PGS':
            T_current = T_current / gear_stage.real_operation_ratio

        # Check if this stage is a ratio stage and update the max sizes accordingly
        if gear_stage.ratio == smallest_shift_ratio or gear_stage.real_operation_ratio == smallest_shift_ratio:
            update_max_sizes(gear_stage)

    return results
```

Code 4.6: size_multistage_gearbox function.

Function: size_gearbox_stage

The function size_gearbox_stage (Code 4.7) handles the sizing of each gear stage by calculating the dimensions and verifying that the gears can withstand the applied forces and stresses.

For simple gears (SG), it starts by calculating the initial module based on the pitch diameter, number of teeth, and helix angle for helical gears. It calculates the number of teeth and diameters for both the driving (pinion) and driven gears. The tangential force is calculated using the applied torque and pitch radius.

For planetary gears (PGS), the sun and ring gear teeth numbers are calculated. The function then calls calculate_PGS_torque_ratios to determine the distribution of torque among the sun, ring, and carrier gears based on the planetary gear's operation mode. The function also calls determine_highest_torque_gear to identify which gear experiences the highest torque, which is crucial for determining the module and tangential force on that gear.

```
def size_gearbox_stage(T, gear_stage, material_strength, security_factor, stage: int) -> dict:
    """
    Determine parameters for a single gearbox stage and track sigma and module.

    Parameters:
    T (float): Torque for the stage.
    gear_stage (GearStage): The GearStage object representing the current stage.
    material_strength (float): The material strength used in stress calculations.
    security_factor (float): The safety factor applied to the stage.
    stage (int): The stage number in the gearbox.

    Returns:
    dict: A dictionary containing the calculated parameters for the stage.
    """
    # Initialize parameters and constants
    ratio = gear_stage.ratio
    realisation = gear_stage.realisation
    operation = gear_stage.operation
    num_planets = gear_stage.num_planets
    pitch_d_initial = 100
    z_initial = 25
    m_initial = 0.0
    beta = 20
    Z_1, Z_2 = 0, 0  # Ensure Z_1 and Z_2 are initialized
    highest_torque_gear = None  # Initialize to None for non-planetary gears (SG)

    if realisation == 'SG':
        # Calculations for simple gear
```

```
        m_initial = pitch_d_initial * math.cos(math.radians(beta)) / z_initial
        z_driving = z_initial
        z_driven = round(z_driving * ratio)
        d_driving = pitch_d_initial
        d_driven = d_driving * ratio
        gear_stage.driving_diameter = d_driving
        gear_stage.driven_diameter = d_driven
        gear_stage.driving_teeth = z_driving
        gear_stage.driven_teeth = z_driven
        F_t = round(T * 2 / (pitch_d_initial * math.cos(math.radians(beta))), 2)
    elif realisation == 'PGS':
        # Calculations for planetary gear
        Z_1 = z_initial
        Z_2 = round(ratio * Z_1)
        ratio, T_sun, T_ring, T_carrier = calculate_PGS_torque_ratios(T, operation, Z_1, Z_2)
        gear_stage.real_operation_ratio = ratio
        m_initial, F_t, highest_torque_gear = determine_highest_torque_gear(T_sun, T_ring, T_carrier, Z_1, Z_2, pitch_d_initial, beta, num_planets)
        T = max(T_sun, T_ring, T_carrier)
    else:
        raise ValueError("Unsupported gear type")

    # Find the module index and start stress analysis
    module_index = find_nearest_higher_module_index(m_initial, first_choice_modules)
    m_initial = first_choice_modules[module_index]
    b, sigma, allowable_stress, Y = initialize_stress_analysis(module_index, F_t, pitch_d_initial, beta, material_strength, security_factor)

    # Refinement loop to find the suitable module
    while sigma > allowable_stress and module_index < len(first_choice_modules) - 1:
        module_index, m_initial, b, z_initial, F_t = refine_stress_parameters(
            module_index, m_initial, z_initial, ratio, realisation, highest_torque_gear, T, num_planets, beta
        )

        sigma = abs((F_t * 1000) / (b * m_initial * Y)) # Recalculate sigma

    if sigma > allowable_stress:
        raise ValueError("No suitable module found that meets the stress condition.")

```

```python
    # Apply final gear dimensions
    gear_stage.module = m_initial
    apply_gear_dimensions(gear_stage, m_initial, realisation, z_initial, Z_1, Z_2, ratio, beta, num_planets)

    print(f"Stage {stage} | Final Module: {m_initial}, Final Sigma: {sigma}, Allowable Stress: {allowable_stress}")

    return compile_stage_results(stage, realisation, F_t, m_initial, pitch_d_initial, b, gear_stage)
```

Code 4.7: size_gearbox_stage function.

Function: calculate_PGS_torque_ratios

For planetary gears, torque distribution varies depending on the operation mode (e.g., sun input, carrier output, or ring fixed). This function presented in Code sample 4.8 computes the torque distribution among the sun, ring, and carrier gears according to the specific operation.

```python
def calculate_PGS_torque_ratios(T, operation, Z_1, Z_2):
    """
    Calculate the torque ratios for a planetary gear system.

    Parameters:
    T (float): Torque input for the system.
    operation (str): The type of planetary gear operation mode.
    Z_1 (int): Number of teeth in the sun gear.
    Z_2 (int): Number of teeth in the ring gear.

    Returns:
    tuple: A tuple containing the gear ratio, torque for the sun gear (T_sun),
           torque for the ring gear (T_ring), and torque for the carrier (T_carrier).
    """
    if operation == '1s':
        # Sun gear is the input, carrier is the output
        ratio = 1 + (Z_2 / Z_1)
        T_carrier = T  # Carrier is the output
        T_sun = T_carrier / ratio  # Sun is the input, reverse the ratio to get input torque
        T_ring = 0  # Ring is stationary

    elif operation == 's1':
        # Carrier is the input, sun gear is the output
        ratio = 1 / (1 + (Z_2 / Z_1))
        T_sun = T  # Sun gear is the output
        T_carrier = T_sun / ratio  # Carrier is the input, reverse the ratio to get input torque
        T_ring = 0  # Ring is stationary

    elif operation == '2s':
```

```
        # Ring gear is the input, carrier is the output
        ratio = -(1 + (Z_1 / Z_2))
        T_carrier = T  # Carrier is the output
        T_ring = T_carrier / ratio  # Ring is the input
        T_sun = 0  # Sun is stationary

    elif operation == 's2':
        # Carrier is the input, ring gear is the output
        ratio = -1 / (1 + (Z_1 / Z_2))
        T_ring = T  # Ring is the output
        T_carrier = T_ring / ratio  # Carrier is the input
        T_sun = 0  # Sun is stationary

    elif operation == '12':
        # Sun gear is the input, ring gear is the output
        ratio = Z_2 / Z_1
        T_ring = T  # Ring is the output
        T_sun = T_ring / ratio  # Sun is the input
        T_carrier = 0  # Carrier is stationary

    else:
        raise ValueError("Unsupported operation mode")

    return ratio, T_sun, T_ring, T_carrier
```

Code 4.8: calculate_PGS_torque_ratios function.

As previously mentioned, the determine_highest_torque_gear function is called just after this function to identify the gear in the planetary gearset that experiences the highest torque. The reason for this step is that the gear with the highest torque will also experience the greatest tangential force at its teeth.

Function: determine_highest_torque_gear

In a planetary gearset, the torques on the sun, planet, and ring gears differ depending on the operational mode and gear ratios. Since the tangential force F_t on the teeth is directly proportional to the torque *T* applied to the gear (according to the Eq. 51), selecting the gear with the highest torque ensures that the tangential force calculated is the largest force acting within the system.

By focusing on the gear with the highest torque, the sizing algorithm ensures that the gear teeth are designed to withstand the maximum load in the system. This approach provides a conservative and reliable estimate for the strength and durability of the gears, as the gear with the highest tangential force will likely experience the most stress during operation.

Therefore, even though the tangential force can be calculated for all the gears in the planetary system, selecting the gear with the highest torque ensures that the calculated force represents the maximum load condition, which is critical for ensuring the reliability of the gearset.

Based on this information, the module is calculated, and the tangential force acting on that gear is estimated.

The module calculation for the highest torque gear depends on the number of teeth and the pitch diameter. The function then calculates the tangential force, which directly affects the bending stress on the gear teeth.

```
def determine_highest_torque_gear(T_sun, T_ring, T_carrier, Z_1, Z_2, pitch_d_initial, beta, num_planets):
    """
    Determine the gear with the highest torque in a planetary gear system.

    Parameters:
    T_sun (float): Torque on the sun gear.
    T_ring (float): Torque on the ring gear.
    T_carrier (float): Torque on the carrier.
    Z_1 (int): Number of teeth on the sun gear.
    Z_2 (int): Number of teeth on the ring gear.
    pitch_d_initial (float): Initial pitch diameter for the gear.
    beta (float): Helix angle in degrees.
    num_planets (int): Number of planet gears.

    Returns:
    tuple: A tuple containing the module, tangential force (F_t), and the gear type with the highest torque.
    """
    max_torque = max(T_sun, T_ring, T_carrier)
    highest_torque_gear = None

    # Set a minimum number of teeth for the planet gears
    min_teeth = 8  # Minimum allowed number of teeth for planet gears

    if max_torque == T_sun:
        highest_torque_gear = "sun"
        m_initial = pitch_d_initial * math.cos(math.radians(beta)) / Z_1
        r_sun = pitch_d_initial / 2
        F_t = round(T_sun / (r_sun * math.cos(math.radians(beta))), 2)

    elif max_torque == T_ring:
        highest_torque_gear = "ring"
        # Apply a correction factor to make the Ring Gear larger than the Sun Gear
        correction_factor_ring = 1.2  # 20% correction factor for the Ring diameter
        pitch_d_initial_ring = pitch_d_initial * correction_factor_ring

        m_initial = pitch_d_initial_ring * math.cos(math.radians(beta)) / Z_2
        r_ring = pitch_d_initial_ring / 2
        F_t = round(T_ring / (r_ring * math.cos(math.radians(beta))), 2)

    elif max_torque == T_carrier:
```

```
        highest_torque_gear = "planet"
        Z_p = round((Z_2 - Z_1) / 2)

        # Ensure the planet gear teeth count doesn't go below the minimum threshold
        if Z_p < min_teeth:
            Z_p = min_teeth

        # Adjustment: reduce the initial pitch diameter for the planet
        reduction_factor = 0.2  # Reduce planet's initial pitch diameter
        pitch_d_initial_planet = pitch_d_initial * reduction_factor

        m_initial = pitch_d_initial_planet * math.cos(math.radians(beta)) / Z_p
        r_planet = pitch_d_initial_planet / 2
        F_t = round((T_carrier / num_planets) / (r_planet * math.cos(math.radians(beta))), 2)

    return m_initial, F_t, highest_torque_gear
```

Code 4.9: determine_highest_torque_gear function.

Function: find_nearest_higher_module_index

The calculated initial module size is often not a standard size, so the function find_nearest_higher_module_index is invoked to find the closest larger module from a predefined list of standard modules[121]. This step ensures that the selected module is feasible in terms of manufacturing.

The function iterates through the list of standard modules and returns the index of the nearest higher module. This module size is then used in subsequent stress analysis and calculations.

Function: initialize_stress_analysis

After determining the module, the next step is to verify whether the gear can handle the applied forces without failure. This is where initialize_stress_analysis is called. This function calculates the bending stress on the gear teeth using the Lewis equation, which is based on the tangential force, module, face width, and the Lewis form factor. The calculated stress is then within the size_gearbox_stage function compared to the allowable stress for the material, adjusted by a safety factor.

The allowable stress is derived from the material strength divided by the safety factor, ensuring that the gears are designed with sufficient margins to handle unexpected loads.

```
def initialize_stress_analysis(module_index, F_t, pitch_d_initial, beta, material_strength, security_factor):
    """
    Initialize stress parameters for a gear stage.

    Parameters:
```

[121] cf.Zdziennicki; Maciejczyk (DESIGN BASIC OF INDUSTRIAL GEAR BOXES), 2011, p. 18.

```
    module_index (int): The index of the module being analyzed.
    F_t (float): The tangential force applied to the gear.
    pitch_d_initial (float): The initial pitch diameter of the gear.
    beta (float): The helix angle in degrees.
    material_strength (float): The strength of the material.
    security_factor (float): The safety factor applied to the stress calculations.

    Returns:
    tuple: A tuple containing the face width (b), calculated stress (sigma), allowable stress, and the Lewis Form Factor (Y).
    """

    # Constants
    Y = 0.35  # Lewis Form Factor, typically based on gear tooth profile
    b = round(((10 * first_choice_modules[module_index]) / math.cos(math.radians(beta))), 1)  # Face width

    # Stress Calculation (sigma)
    sigma = abs((F_t * 1000) / (b * first_choice_modules[module_index] * Y))  # Stress in MPa
    allowable_stress = material_strength / security_factor

    # Log initial values for debugging purposes
    print(f"Initial Sigma: {sigma}, Allowable Stress: {allowable_stress}, Initial Module: {first_choice_modules[module_index]}")

    return b, sigma, allowable_stress, Y
```

Code 4.10: initialize_stress_analysis function.

Function: refine_stress_parameters

If the calculated bending stress exceeds the allowable stress, the function refine_stress_parameters is invoked. This function increases the module size iteratively by selecting the next larger standard module, recalculating the tangential force and the face width. It also adjusts the number of teeth as needed to maintain a proper ratio between gears.

The function repeats this process of recalculating and checking until the bending stress is within the allowable limits. This iterative refinement ensures that the gears are sized appropriately to handle the loads without failure.

```
def refine_stress_parameters(module_index, m_initial, z_initial, ratio, realisation, highest_torque_gear, T, num_planets, beta):
    """
    Update stress parameters during the iteration to find a suitable module size.

    Parameters:
    module_index (int): The index of the module being analyzed.
    m_initial (float): The initial module value.
```

```python
    z_initial (int): The initial number of teeth on the gear.
    ratio (float): Gear ratio for the stage.
    realisation (str): The type of gear realization (SG or PGS).
    highest_torque_gear (str): The gear type with the highest torque.
    T (float): The torque being applied to the gear.
    num_planets (int): Number of planet gears in the system.
    beta (float): Helix angle in degrees.

    Returns:
    tuple: A tuple containing the updated module index, module size, face width, number of teeth, and tangential force.
    """

    # Move to the next higher module in the list
    module_index += 1
    if module_index >= len(first_choice_modules):
        raise ValueError("No suitable module found that meets the stress condition.")

    m_initial = first_choice_modules[module_index]
    b = round(((10 * m_initial) /  math.cos(math.radians(beta))), 1)  # Update face width

    # Increase the teeth count to maintain the ratio
    z_initial += 1

    if realisation == 'SG':  # Simple Gear Calculation
        z_driving = z_initial
        z_driven = round(z_driving * ratio)
        pitch_diameter = m_initial * z_driving / math.cos(math.radians(beta))
        pitch_radius = pitch_diameter / 2
        F_t = round(T / (pitch_radius * math.cos(math.radians(beta))), 2)

    elif highest_torque_gear == "sun":  # Refinement for Sun Gear in PGS
        Z_1 = z_initial
        Z_2 = round(Z_1 * ratio)
        pitch_diameter = m_initial * Z_1 / math.cos(math.radians(beta))
        pitch_radius = pitch_diameter / 2
        F_t = round(T / (pitch_radius * math.cos(math.radians(beta))), 2)

    elif highest_torque_gear == "ring":  # Refinement for Ring Gear in PGS
        Z_2 = round(Z_1 * ratio)
        Z_1 = round(Z_2 / ratio)
        Z_p = round((Z_2 - Z_1) / 2)
        pitch_diameter = m_initial * Z_2 / math.cos(math.radians(beta))
        pitch_radius = pitch_diameter / 2
```

```
        F_t = round(T / (pitch_radius * math.cos(math.radians(beta))), 2)

    elif highest_torque_gear == "planet":  # Refinement for Planet Gear in PGS
        Z_1 = z_initial
        Z_2 = round(Z_1 * ratio)
        Z_p = round((Z_2 - Z_1) / 2)
        # Ensure planet teeth remain above the minimum
        min_teeth = 8
        if Z_p < min_teeth:
            Z_p = min_teeth
        pitch_diameter = m_initial * Z_p / math.cos(math.radians(beta))
        pitch_radius = pitch_diameter / 2
        F_t = round((T / num_planets) / (pitch_radius * math.cos(math.radians(beta))), 2)

    return module_index, m_initial, b, z_initial, F_t
```

Code 4.11: refine_stress_parameters function.

Function: apply_gear_dimensions

Once the final module size is determined, the function apply_gear_dimensions updates the calculated gear dimensions for the stage. This includes updating parameters such as the number of teeth and diameters for the driving and driven gears in simple gear stages or the sun, ring, and planet gears in planetary gear stages.

For planetary gears, the diameters of the sun and ring gears are computed based on the module and the number of teeth, while the planet diameter is calculated as the difference between the ring and sun diameters divided by two.

Function: update_max_sizes

In a gearbox that includes a shift stage, different gear ratios can be attached to that stage, meaning the gearbox can operate in multiple configurations. Each of these configurations applies varying conditions to the gear sets in the remaining stages of the gearbox. Consequently, the gears in these stages must be sized not just for one ratio but for all possible ratios that the shift stage introduces.

For each configuration (or gear ratio), the program calculates the size of the gears or planetary sets in both the shift stage and the corresponding gears in the other stages. This allows the algorithm to assess whether the design can handle the different torque, speed, and load requirements posed by each configuration. Since different ratios will place varying levels of stress on the gears, the dimensions calculated for each configuration may differ.

To ensure that the gearbox design remains reliable regardless of which configuration is active, the program must track the most demanding conditions encountered during the sizing process. This is when the update_max_sizes function is called within the main function. After the size of each gear set is calculated for a particular ratio, update_max_sizes compares the current dimensions (such as module, driving diameter, number of teeth, etc.) with the previously recorded maximum values.

- If the current gear size exceeds the previously recorded size, update_max_sizes updates the maximum values accordingly.
- If not, the previous maximum value is retained.

This ensures that by the end of the sizing process, the largest and most robust gear sizes are kept for each stage. These maximum values are crucial because they ensure that the gearbox will be able to handle the most demanding conditions imposed by any of the configurations (gear ratios) generated by the shift stage. Essentially, the gearbox is sized for the worst-case scenario, ensuring its reliability across all possible configurations.

4.4 Output Generation and Visualization

The final phase of the tool's implementation involves generating and interpreting the outputs, which are essential for evaluating the gearbox design in terms of both physical dimensions and performance. These outputs include gear sizes, stress levels, and calculated torque and power losses. The tool provides these outputs as both numerical data and visual representations, enabling engineers to assess the feasibility and efficiency of different gearbox configurations. This section explains how the outputs are generated and their relevance to gearbox design.

4.4.1 Gear Sizing Results

The primary output from the gross sizing algorithm is the set of gear dimensions for each stage of the gearbox. The final gear sizing results are presented in a format that allows the engineer to quickly understand the dimensions and specifications for the entire gearbox configuration. The output includes the following key parameters for each gear:

- **Module size (m):** A measure of gear size, which affects its ability to handle the required torque.
- **Number of teeth (z):** Determines the gear ratio and directly influences the tangential forces acting on the gear teeth.
- **Pitch diameters (d):** The diameters at which the gears engage, crucial for understanding the physical size of the gearbox.
- **Face width (b):** The width of the gear face, which affects how loads are distributed across the gear teeth.

Format of Final Sizing Results

The final sizing results are structured to provide comprehensive data for all stages of the gearbox, with special attention to how shift stages are handled. In a shiftable gearbox, different gear pairs or planetary gearsets are used to produce multiple gear ratios, allowing the gearbox to shift between them and handle varying output torque and speed requirements. Therefore, for shift stages, the dimensions of the gears composing each of the different shiftable ratios are displayed, while for the rest of the stages, only the dimensions sized for the most demanding conditions are presented.

1. **Shift Stage Sizing:**
    - In a shift stage, there are multiple gears or gearsets that enable the gearbox to shift between different speeds or gear ratios. The tool calculates and displays the dimensions for each of these gears or gearsets separately, as each ratio corresponds to a different configuration of gears within the gearbox.
    - The output shows the gear dimensions for each shiftable ratio, including the module, number of teeth, pitch diameter, and face width for each gear in the stage.
    - This is crucial for ensuring that each gear pair or planetary gearset within the shift stage is appropriately sized to handle the varying torque and speed conditions for each ratio.

For each shiftable ratio in the shift stage, the dimensions are provided separately, showing how the gearbox adapts to different speed and torque conditions by engaging different gear pairs or planetary gearsets. This allows the engineer to evaluate whether the gears are properly dimensioned for each speed or ratio within the shift stage.

2. **Other Stages Sizing:**
    - For stages that are not part of the shift mechanism (such as planetary or simple gear stages), only the dimensions calculated under the most demanding conditions are shown. This ensures that the gears in these stages are robust enough to handle the highest loads or torque.
    - By focusing on the worst-case scenario for these stages, the output ensures that the gearbox will function reliably under the most extreme conditions.

In summary, the final sizing results are presented in a way that reflects the multiple configurations within the shift stage, while ensuring that the rest of the gearbox is sized for the most demanding conditions. This approach provides the engineer with a complete view of the gearbox design, including the dimensions required for each shiftable ratio and the most critical stages. Code sample 4.12 below illustrates how the results are displayed in the console.

```
Final Sizing Results:

Stage 2 (Simple Gear):

  Driving Gear Diameter: 223 mm

  Driving Gear Teeth: 30

  Driven Gear Diameter: 447 mm

  Driven Gear Teeth: 60

  Module: 7.00 mm
```

```
Speed 1, Shift Ratio 2.92:
Stage 1 (Planetary Gear):
  Sun Diameter: 106 mm
  Sun Teeth: 25
  Planet Diameter: 102 mm
  Planet Teeth: 24
  Ring Diameter: 311 mm
  Ring Teeth: 73
  Module: 4.00 mm

Speed 2, Shift Ratio 3.5:
Stage 1 (Planetary Gear):
  Sun Diameter: 93 mm
  Sun Teeth: 25
  Planet Diameter: 117 mm
  Planet Teeth: 32
  Ring Diameter: 328 mm
  Ring Teeth: 88
  Module: 3.50 mm
```

Code 4.12: Example Output for Final Sizing Results.

4.4.2 Loss Calculation Outputs

In addition to sizing, the tool calculates the load-independent and load-dependent losses, which are crucial for assessing the overall performance of the gearbox. These losses are reported as:

- **Total torque losses:** These reflect the losses due to inefficiencies in gear meshing, bearings, and other components. The calculated torque losses are particularly useful for understanding how much torque is lost throughout the transmission stages.
- **Total power losses:** The power losses reflect the energy dissipated due to inefficiencies in the transmission, which affects the overall efficiency of the gearbox.
- **Worst-case input torque:** The tool also calculates the worst-case input torque needed from the motor to compensate for the total losses throughout the gearbox. This is important for determining the input requirements for the motor, ensuring that the motor can provide enough torque to overcome losses and deliver the necessary output.

The purpose of these outputs is to provide the engineer or user with a comprehensive view of the gearbox's total losses under various operating conditions. This enables the user to evaluate whether the torque losses are acceptable for the intended application or to compare different gearbox configurations. By comparing the results of multiple configurations, the engineer can select the gearbox design that best balances efficiency and torque transmission with the specific requirements of the vehicle or application.

Worst-Case Input Torque Calculation

The worst-case input torque is a critical output, as it represents the maximum torque required from the motor to overcome losses and ensure the gearbox delivers the desired output torque. This value is derived by adding the total losses to the desired output torque and calculating the necessary input torque under the most demanding operating conditions. It provides valuable insight into the motor requirements for the gearbox configuration.

4.4.3 Visual Representation of Losses

To facilitate the interpretation of loss calculations, the tool generates heatmaps that illustrate the variation of power and torque losses across different RPM and torque conditions. These visualizations make it easier to compare different configurations and assess the overall performance of the gearbox.

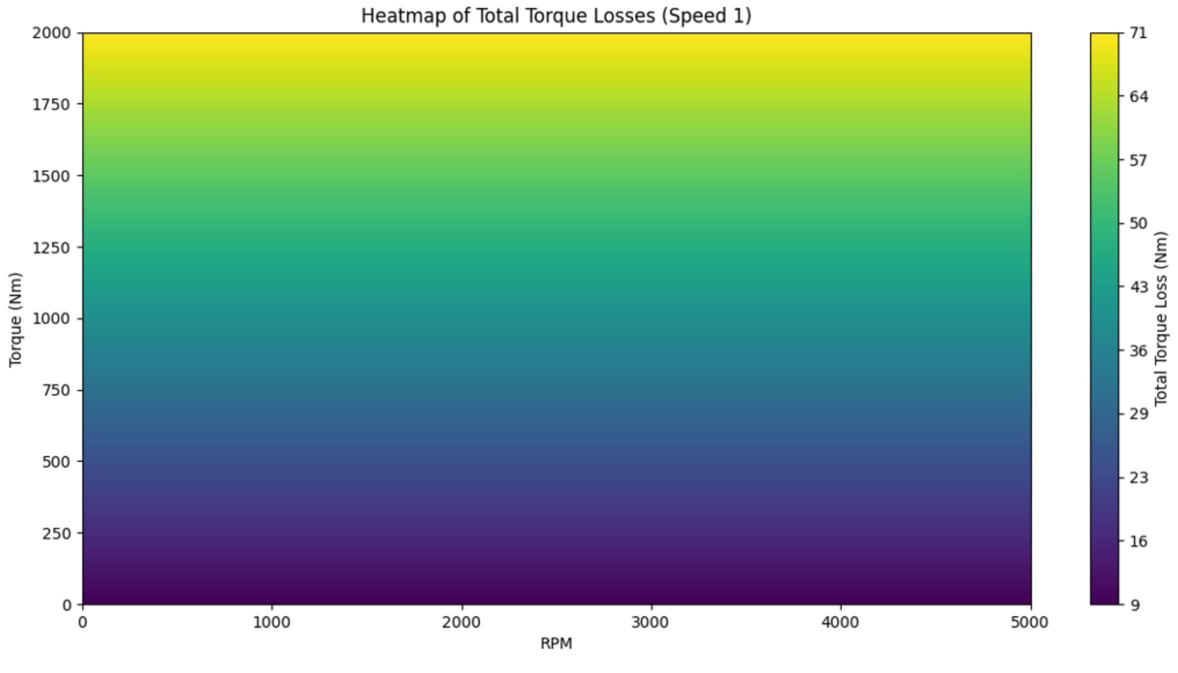

Figure 4.6: Example plot of Heatmap of Total Torque Losses.

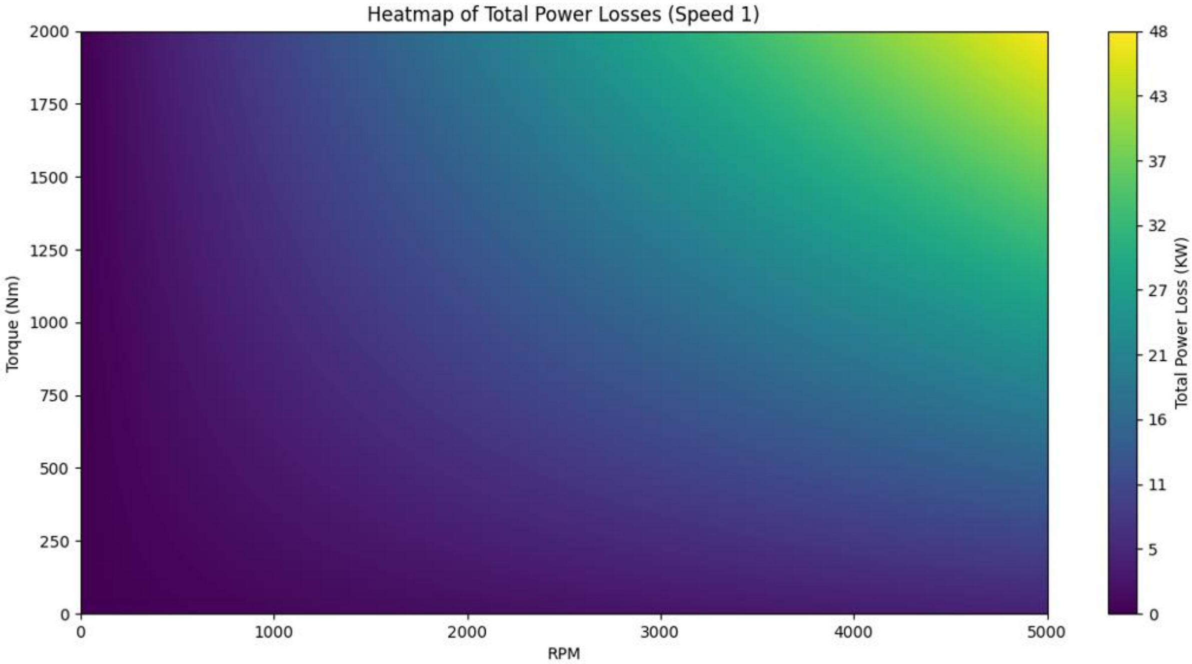

Figure 4.7: Example plot of Heatmap of Total Power Losses.

These plots provide an intuitive way for engineers to assess whether the total losses are acceptable for the application and compare the efficiency of different configurations. The visual representations allow users to quickly identify configurations with minimal losses or to investigate the conditions under which losses become significant.

4.4.4 Output Overview and Practical Use

The outputs generated by the tool serve two main purposes:

1. **Space and Fit Assessment:** The gear sizing outputs provide the dimensions of the gearbox components, which the engineer can use to evaluate whether the gearbox fits within the physical constraints of the vehicle or machinery.
2. **Performance and Efficiency Comparison:** The torque and power loss calculations allow the user to assess whether the gearbox configuration's losses are acceptable for the intended application. Moreover, by comparing the results of different gearbox configurations, it can be determined which design provides the best balance between efficiency and performance, enabling informed decision-making based on the specific requirements.

In summary, the outputs of the tool provide engineers with the necessary data to make critical decisions during the early stages of gearbox design. The gear sizing outputs help assess physical feasibility, while the loss calculations enable a detailed evaluation of gearbox efficiency across different configurations. The calculation of worst-case input torque ensures that the motor requirements are adequately met. By presenting these results in both numerical and visual formats, the tool supports the comparison of multiple designs, ultimately guiding the selection of the most suitable gearbox configuration for a given application.

5 Validation of the Tool

This chapter focuses on the validation of the gearbox loss model and the sizing algorithm used for early-stage transmission design in electric powertrains. The validation process ensures that the models align with real-world performance data, enabling their reliable use in transmission design when detailed component data is unavailable.

The validation of the gearbox loss model builds upon two complementary approaches. First, the model's validation by its authors demonstrates its fundamental reliability. However, to ensure that the Python implementation is free of errors and accurately represents the model, further validation is conducted using experimental efficiency data. This combined approach ensures that both the model and its implementation align with real-world performance.

Additionally, the chapter reviews the sizing algorithm to verify its suitability for early-stage transmission design.

5.1 Validation of the Gearbox Loss Model Implementation

The gearbox loss model presented by Krüger et al.[122] was validated through a series of experiments, including a Worldwide Harmonised Light-Duty Vehicles Cycle (WLTC) simulation. The loss model was applied to a two-staged, one-speed simple gear transmission within an electric powertrain, and its results were benchmarked against measured data.

Specifically, the validation process involved comparing the model's predicted transmission efficiency to an experimentally obtained efficiency map. The model's results showed a cumulative deviation of -0.6% by the end of the simulation, indicating that the loss model underestimates losses slightly but within acceptable limits. This slight deviation demonstrates the model's reliability for estimating transmission losses during the early stages of electric powertrain development, where detailed design data may not be available.[123]

While this original validation confirms the model's theoretical soundness, additional validation is necessary to ensure that the Python implementation accurately replicates the model's performance.

To complement the model validation, an independent validation was conducted using experimental efficiency data obtained from an external study[124]. The gearbox under investigation is part of a dual-motor electric drivetrain, where two electric motors are connected to a common input shaft that drives the gearbox. The gearbox itself is a two-stage system utilizing helical simple gears, which then transfers power to the differential. Although the system includes two motors, because they are both connected to the same input shaft, the gearbox experiences the combined torque as if it were a single motor application. This configuration allows the loss model, originally designed for single motor applications, to be effectively applied to this dual-

[122] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022.

[123] cf.Krüger et al. (Design and optimisation of single motor electric powertrains considering different transmission topologies), 2022, p. 13.

[124] cf.Břoušek; Zvolský (Experimental study of electric vehicle gearbox efficiency), 2018.

motor setup. This validation aimed to assess how well the Python implementation of the loss model aligns with real-world data.

Experimental Data Overview:

The experimental data from the study measured gearbox efficiency under different operating conditions with two oil charge levels (500g and 820g). The efficiency values were recorded for different combinations of input speed and output torque.

Table 5.1: Experimental Efficiency Data for 500g Oil Charge.[125]

Input	20 Nm	40 Nm	60 Nm	80 Nm
500 rpm	0.955	0.99	0.99	0.99
1000 rpm	0.92	0.99	0.99	0.99
1500 rpm	0.88	0.985	0.99	0.99
2000 rpm	0.91	0.98	0.99	0.99
2500 rpm	0.88	0.955	0.975	0.98
3000 rpm	0.86	0.94	0.96	0.97

Table 5.2: Experimental Efficiency Data for 820g Oil Charge.[126]

Input	20 Nm	40 Nm	60 Nm	80 Nm
500 rpm	0,92	0,97	0,98	0,98
1000 rpm	0,91	0,97	0,98	0,98
1500 rpm	0,89	0,97	0,98	0,98
2000 rpm	0,88	0,97	0,97	0,98
2500 rpm	0,88	0,95	0,95	0,97
3000 rpm	0,855	0,94	0,945	0,96

Program Results Overview:

A simulation under the same operating conditions was done in the Python program, obtaining the power losses for each of the cases, calculating then with these values the efficiency of the gearbox. Since the program is intended to work with rough complexity estimations, it does not differentiate between oil charge scenarios, and the results are presented in Table 5.3.

[125] cf.Břoušek; Zvolský (Experimental study of electric vehicle gearbox efficiency), 2018, p. 4.
[126] cf.Břoušek; Zvolský (Experimental study of electric vehicle gearbox efficiency), 2018, p. 4.

Table 5.3: Simulated Efficiency Data.

Input	20 Nm	40 Nm	60 Nm	80 Nm
500 rpm	0,94	0,96	0,97	0,97
1000 rpm	0,94	0,96	0,97	0,97
1500 rpm	0,94	0,96	0,97	0,97
2000 rpm	0,94	0,96	0,97	0,97
2500 rpm	0,94	0,96	0,97	0,97
3000 rpm	0,94	0,96	0,97	0,97

Key Observations from the Efficiency Data:

The real-world data in Table 5.1 and Table 5.2 presents several important trends that serve as the foundation for validating our model:

1. **Efficiency Trends Across Torque:**

   The efficiency of the gearbox generally increases with torque at each fixed RPM level. This trend is consistent across both datasets (500g and 820g oil levels), indicating that the gearbox operates more efficiently under higher load conditions. This behavior is typical of mechanical systems where higher loads can reduce the relative impact of frictional and other parasitic losses. The program captures this trend reasonably well, as seen in the simulated data.

2. **RPM Sensitivity:**

   The data shows a tendency for efficiency to decrease as RPM increases, particularly at lower torque levels (e.g., 20 Nm). However, this trend becomes less pronounced as the torque increases, suggesting that at higher torques, the influence of RPM on efficiency diminishes. This observation is crucial to understanding the limitations of the model we are using. While the model primarily considers torque and does not explicitly factor in RPM variations, as discussed earlier in the text, it still provides reliable results that are consistent with the general trends observed in the data.

3. **Effect of Oil Levels:**

   When comparing the two datasets, it is evident that increasing the oil level results in slight reductions in efficiency, especially at higher torque levels. This could be attributed to increased oil drag, which might outweigh the benefits of improved lubrication. While the current program does not explicitly account for oil level changes, this observation aligns with our understanding that detailed design parameters are not the focus at this stage. Instead, the program aims to provide reliable estimates based on rough complexity estimations.

   Furthermore, it is important to note that the loss model we are implementing takes a different approach, as it considers the use of oil pumps to circulate the lubricant. This approach differs from a model based on static oil levels within the gearbox. The presence of oil pumps could influence the efficiency outcomes, as it actively manages lubrication and cooling, which may lead to different efficiency trends compared to a gearbox simply operating with fixed oil levels. This distinction might explain certain deviations observed between the datasets and the simulated results.

4. **Anomalies in the Data:**

   A notable anomaly occurs at 1500 RPM and 20 Nm torque, where the efficiency drops unexpectedly in the 500g oil charge dataset (Table 5.1). This outlier suggests either a measurement error or a specific operating condition that adversely affected performance. Such anomalies are important to consider when validating our model, as they may indicate areas where real-world performance deviates from idealized behavior. The program's consistent results at this point suggest that it may not fully capture such nuanced behaviors, which is a potential area for improvement, though not critical for the current application.

Potential Sources of Discrepancies:

It is also important to recognize that some small discrepancies in the efficiency values between the simulated and experimental data may be due to the incomplete input data provided in the experimental study. The document from which the real-world data was extracted did not specify all the input values required by the program, such as the exact number of elements contributing to drag torque. Consequently, these inputs had to be estimated for the simulation.

If the number of elements that contribute to drag torque was either overestimated or underestimated during the simulation, this could lead to discrepancies in the simulated efficiency values. An overestimation would result in a slight overestimation of drag torque, which would decrease the simulated efficiency values across all torque levels. Conversely, underestimation would increase simulated efficiency. This effect would be more noticeable at lower torque levels, where drag torque represents a larger proportion of the total torque and would diminish as the torque increases. This potential source of discrepancy highlights the importance of accurate input data in achieving precise simulation results. Which relies in the data available on the gearbox draft.

Error Analysis:

Given that the program does not differentiate between oil charges, the validation focused on comparing the program’s results with each set of experimental data individually. Absolute errors were calculated for each corresponding data point.

The accuracy of the Python implementation of the loss model was evaluated by comparing the experimental efficiency data with the simulated efficiency values. The absolute error was calculated for each combination of RPM and torque values in both the 500g and 820g oil charge scenarios. Below is an example that represents the maximum deviation observed in the dataset:

At 1500 RPM and 20 Nm:

- **500g Oil Charge**:
  - Experimental Efficiency: 0.88
  - Simulated Efficiency: 0.94
  - Absolute Error: 0.06

- **820g Oil Charge**:
    - Experimental Efficiency: 0.89
    - Simulated Efficiency: 0.94
    - Absolute Error: 0.05

Mean Absolute Error (MAE) Calculation

The MAE was calculated separately for the 500g and 820g oil charge scenarios by averaging the absolute errors for each data point.

- **500g Oil Charge MAE**:
    - Total Absolute Error: 0.578
    - Number of Data Points: 24
    - MAE = 0.578 / 24 = 0.024
- **820g Oil Charge MAE**:
    - Total Absolute Error: 0.508
    - Number of Data Points: 24
    - MAE = 0.508 / 24 = 0.021

Overall Accuracy

- **500g Oil Charge**: The mean absolute error (MAE) across all RPM and torque levels was calculated to be **0.024**. This represents the average difference between the experimental data and the simulated efficiency predictions for the 500g oil charge case.
- **820g Oil Charge**: For the 820g oil charge, the mean absolute error (MAE) was calculated to be **0.021**, showing that the model was slightly more aligned with the experimental data under higher oil charge conditions.

The absolute errors in both the 500g and 820g oil charge datasets show that the model captures the overall efficiency trends well, with only minor deviations. The maximum observed deviation, 0.06 for the 500g charge and 0.05 for the 820g charge, occurs at the lowest torque level (20 Nm). In the 500g case, this deviation coincides with an anomaly in the experimental data at 1500 RPM and 20 Nm, where the efficiency unexpectedly drops. Despite this, the loss model remains consistent across various operating conditions.

On average, the deviations between the simulated and experimental data are around 2% for both oil charge scenarios, indicating that the Python implementation of the loss model provides a reliable estimation of gearbox efficiency.

While the current validation demonstrates the model's accuracy for early-stage gearbox design, further validation using real-world data from electric commercial vehicle gearboxes could provide additional insights. However, such data is typically proprietary and not publicly accessible. Despite this limitation, the current validation using available experimental data offers reliable and valuable results, making the model a useful tool for early-stage development and design optimization.

5.2 Validation of the Sizing Algorithm

The gross sizing algorithm is designed to provide a quick and practical estimation of gearbox dimensions, primarily focusing on whether a proposed configuration is viable within given space and performance constraints. While the validation of this algorithm is not based on real-world data, its validity can be supported through its reliance on established mechanical principles, particularly the **Lewis equation**, which governs gear strength and bending stress.

5.2.1 Basis for the Sizing Algorithm's Validity

The sizing algorithm's validity is grounded in its use of the Lewis equation (Eq. 52), a key tool in gear design that calculates the bending stress on gear teeth. This ensures that the gears are designed to withstand operational loads without failure. By focusing on critical factors such as the tangential force, face width, and module, the algorithm adheres to well-established mechanical principles. Additionally, the inclusion of a safety factor accounts for uncertainties in material properties and operational conditions, ensuring that the estimated gear sizes have sufficient strength for reliable performance.

5.2.2 Simplifications and Practical Application

Although the algorithm effectively handles helical and planetary gears, it simplifies the process by assuming all gears are helical, even in stages where bevel or hypoid gears might be used. While this is not fully accurate, it provides useful insights during early-stage design. If the configuration is found feasible using these assumptions, the design is likely robust enough to handle the required loads. Conversely, if the sizing indicates infeasibility, it prompts further refinement.

This approach ensures that the gearbox configuration remains within viable limits, even if adjustments are needed later for specific gear stages. Despite these simplifications, the algorithm remains a practical tool for early-stage feasibility analysis.

5.2.3 Validation Through Established Design Principles

The validity of the sizing algorithm can be attributed to its foundation in well-established gear design principles. By leveraging the Lewis equation and standard mechanical practices, the algorithm offers reliable estimates of gear size. This theoretical grounding supports the idea that the algorithm's predictions are mechanically sound, even without real-world data for direct validation.

While the algorithm simplifies certain elements, its adherence to proven engineering methods ensures that it delivers reliable results for the preliminary design of gearboxes. This makes it a useful tool for early-stage design, where detailed data may not yet be available.

5.2.4 Assumptions and Iterative Approach

The algorithm operates under several key assumptions:

- **Uniform Load Distribution**: It assumes that the load is evenly distributed across the gear teeth, which simplifies the process but may not fully reflect real-world conditions.
- **Ideal Material Properties**: The algorithm uses idealized material properties, not accounting for variations due to temperature or wear.

Despite these assumptions, the algorithm includes an iterative process to refine gear dimensions if the calculated stress exceeds allowable limits, ensuring that the final design is robust enough to handle the expected operational loads.

5.2.5 Conclusion

The gross sizing algorithm, built on the Lewis equation and supported by well-established engineering principles, provides reliable estimates of gearbox dimensions for early-stage design. While the algorithm simplifies certain aspects of gear design, such as treating all gears as helical, these simplifications are appropriate for initial feasibility assessments. The tool's iterative approach ensures that the design can be refined to meet safety and operational requirements.

As with the loss model validation, further validation using real-world data from electric commercial vehicle gearboxes would provide additional insights and enhance the accuracy of the sizing algorithm. However, due to the proprietary nature of such data, it is often not publicly accessible. Despite this limitation, the current validation process, relying on sound mechanical principles, is robust and reliable for early-stage gearbox design.

6 Summary and Outlook

The primary objective of this thesis was to develop and validate a Python-based tool capable of estimating gearbox torque losses and performing gross sizing for electric vehicle transmissions, with a specific focus on early-stage design. This tool integrates two key models: a gearbox loss model and a gross sizing algorithm, both of which are grounded in well-established mechanical principles and aimed at enabling the efficient evaluation of gearbox configurations in electric vehicles.

The gearbox loss model was designed to calculate torque losses under varying operational conditions, allowing for a realistic assessment of how different factors affect the overall efficiency of a gearbox. The model was validated against experimental data from a real gearbox, ensuring that its predictions were accurate and reliable. The results demonstrated a strong alignment with the experimental data, with an average deviation of approximately 2%. This level of accuracy confirms that the loss model is sufficiently precise for use in early-stage transmission design. The validation process has demonstrated that the tool is capable of providing valuable insights into gearbox performance, making it a highly effective resource for engineers working in electric drivetrain development.

In addition to its accuracy, the tool showed impressive performance in terms of its speed. The tool allows for rapid calculations, which is critical in iterative design processes where engineers need quick feedback on various configurations. The clear and actionable results generated by the tool enable engineers to make informed decisions quickly, supporting the iterative nature of early-stage design. Although this validation was successful, it is important to note that future access to real-world data from commercial electric vehicle gearboxes would allow for further refinement of the model. Such proprietary data, while often difficult to obtain, could significantly enhance the accuracy and applicability of the tool, making it an even more valuable asset for gearbox design.

The gross sizing algorithm was developed using the Lewis equation, a foundational principle in gear design, to provide quick and practical estimations of gearbox dimensions. This algorithm focuses on determining whether proposed configurations meet critical performance and space constraints. Although certain simplifications were made in the design process to enhance efficiency, the algorithm has proven to be highly reliable for feasibility assessments in the early stages of gearbox design. The validation, which was based on theoretical mechanical principles, confirmed that the algorithm provides dependable estimates for gear sizing. The tool's ability to provide rapid feedback on different design scenarios adds tremendous value to the design process, particularly when engineers are working with tight timelines. As with the loss model, the gross sizing algorithm would also benefit from further validation with real-world data. This would ensure that the algorithm remains robust and adaptable as transmission technologies continue to evolve.

Looking ahead, there are several opportunities to improve the tool's relevance and functionality. One area of enhancement could be expanding the tool's ability to handle a wider variety of transmission types would be a valuable upgrade. As the electric vehicle industry continues to grow, the diversity of transmission systems is likely to increase. Ensuring that the tool remains adaptable to evolving transmission technologies will be critical to maintaining its relevance and effectiveness in the long term.

In conclusion, the Python tool developed in this thesis offers a solid foundation for calculating gearbox torque losses and performing gross sizing in early-stage design. The tool's rapid calculation times, ease of use, and clear, actionable output have proven to be key factors in its effectiveness within the design process. By providing engineers with reliable data quickly, the tool supports iterative design workflows and helps in optimizing gearbox configurations tailored to the needs of electric commercial vehicles. While the current implementation meets the intended objectives, future improvements—particularly in terms of usability, data validation, and expanding its analytical scope—will further increase its value. These enhancements will ensure that the tool remains a vital resource in the ongoing transition towards more sustainable and efficient electric vehicle transmissions, ultimately helping to accelerate innovation in electric drivetrain design.

7 Bibliography

Adam Lundin; Peter Mårdestam (Efficiency Analysis of a Planetary Gearbox): *Efficiency Analysis of a Planetary Gearbox*. Bachelor of Science. Linköping, 2010

Alexei Morozov, Kieran Humphries, Ting Zou, Tanvir Rahman and Jorge Angeles (Design, Analysis, and Optimization of a Multi-Speed Powertrain for Class-7 Electric Trucks), *Design, Analysis, and Optimization of a Multi-Speed Powertrain for Class-7 Electric Trucks*. SAE International Journal of Alternative Powertrains, Vol.Vol. 7, 2018, No. 1

Beia Spiller, Nafisa Lohawala, and Emma DeAngeli (Medium- and Heavy-Duty Vehicle Electrification: Challenges, Policy Solutions, and Open Research Questions), *Medium- and Heavy-Duty Vehicle Electrification: Challenges, Policy Solutions, and Open Research Questions*, 2023

Borsboom, O.; Mooy, T. d.; Salazar, M.; Hofman, T. (Control and Design Optimization of an Electric Vehicle Transmission Using Analytical Modeling Methods): *Control and Design Optimization of an Electric Vehicle Transmission Using Analytical Modeling Methods*, 24/10/2022

Brenna, M.; Foiadelli, F.; Leone, C.; Longo, M.; Zaninelli, D. (Feasibility Proposal for Heavy Duty Farm Tractor), *Feasibility Proposal for Heavy Duty Farm Tractor*: 2018 International Conference of Electrical and Electronic Technologies for Automotive. 2018 International Conference of Electrical and Electronic Technologies for Automotive, 7/9/2018 - 7/11/2018: IEEE, 2018 - 2018, p. 1-6

Břoušek, J.; Zvolský, T. (Experimental study of electric vehicle gearbox efficiency), *Experimental study of electric vehicle gearbox efficiency*. In: MATEC Web Conf., Vol.234, 2018, p. 5

Budynas, R. G., & Nisbett, J. K. (ed.) (Mechanical Engineering Design), *Mechanical Engineering Design.* 9ed., 2011

Christopher Pohlkamp, Anita Oh, Paul Nguyen, Julien Bert (The Future of Buses and Light Commercial Vehicles Is Electric), *The Future of Buses and Light Commercial Vehicles Is Electric*, 2022

Crissey, A.Inside Electric Truck Transmissions, *Inside Electric Truck Transmissions*. In: Tomorrows Technician, 22.04.2020

Gözen, E.; Çevirgen, M. S.; Özgül, E. (Transmission speed and ratio optimization for heavy-duty electric truck), *Transmission speed and ratio optimization for heavy-duty electric truck*. In: Heliyon, Vol.8, 2022, 8, e10028

Guo, D.; Wen, G.; Wang, Y.; Luo, D. (A Theoretical and Experimental Study on the Power Loss of Gearbox Based on Dimensionless Analysis), *A Theoretical and Experimental Study on the Power Loss of Gearbox Based on Dimensionless Analysis*. In: J. Tribol, Vol.145, 2023, 10

Hasan, M. M.; El Baghdadi, M.; Hegazy, O. (Energy Management Strategy in Electric Buses for Public Transport using ECO-driving), *Energy Management Strategy in Electric Buses for Public Transport using ECO-driving*: 2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER). 2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), 9/10/2020 - 9/12/2020: IEEE, 2020, p. 1-8

Hilgers, M. (Transmissions and drivetrain design):
Transmissions and drivetrain design. (Reihe: Commercial vehicle technology. Second editioned. Berlin, Germany: Springer Vieweg, 2023

Joseph E. Shigley; Charles R. Mischke (ed.) (Standard Handbook of Machine Design), *Standard Handbook of Machine Design.* 2ed., 1996

Juvinall, R. C.; Marshek, K. M. (Fundamentals of machine component design):
Fundamentals of machine component design. 5th ed.ed. Hoboken NJ: John Wiley & Sons, 2012

Krüger, B.; Keinprecht, G.; Filomeno, G.; Dennin, D.; Tenberge, P. (Design and optimisation of single motor electric powertrains considering different transmission topologies), *Design and optimisation of single motor electric powertrains considering different transmission topologies*. In: Mechanism and Machine Theory, Vol.168, 2022, p. 21

Lacock, S.; Du Plessis, A. A.; Booysen, M. J. (Electric Vehicle Drivetrain Efficiency and the Multi-Speed Transmission Question), *Electric Vehicle Drivetrain Efficiency and the Multi-Speed Transmission Question*. In: World Electric Vehicle Journal, Vol.14, 2023, 12, p. 1-16

Lajunen, A.; Suomela, J.; Pippuri, J.; Tammi, K.; Lehmuspelto, T.; Sainio, P. (Electric and Hybrid Electric Non-Road Mobile Machinery – Present Situation and Future Trends), *Electric and Hybrid Electric Non-Road Mobile Machinery – Present Situation and Future Trends*. In: WEVJ, Vol.8, 2016, 1, p. 172-183

Lynwander, P. (Gear Drive Systems: Design and Application):
Gear Drive Systems: Design and Application

Mohanraj, R.; Elangovan, S.; Pratheesh Kumar, S.; Venkateshan, K.; Manojh Kumar, R.; Sathish Kumar, N. (Theoretical and Numerical Analysis of Bending Stress on Spur Gears), *Theoretical and Numerical Analysis of Bending Stress on Spur Gears*. In: Sivaram, N. M.; Sankaranarayanasamy, K.; Davim, J. Paulo (ed.): Advances in Manufacturing, Automation, Design and Energy Technologies: *Proceedings from ICoFT 2021.* International Conference on Future technologies in Manufacturing, Automation, Design and Energy. 1st ed. 2023 Aufl. Singapore: Springer Nature Singapore; Imprint Springer, 2023, p. 519-528

Molotnikov, V.; Molotnikova, A. (Shaft and Axle Supports), *Shaft and Axle Supports*. In: Molotnikov, V.; Molotnikova, Antonina (ed.): Theoretical and Applied Mechanics. 1 Aufl. Cham: Springer, 2023, p. 555-570

Naunheimer, H.; Fietkau, P.; Lechner, G. (Automotive transmissions): *Automotive transmissions*. *Fundamentals, selection, design, and application.* 2nd ed.ed. Heidelberg, New York: Springer, 2011

Niijjaawan, N.; Niijjaawan, R. (Gears), *Gears*. In: Niijjaawan, N.; Niijjaawan, Rasshmi (ed.): Modern approach to maintenance in spinning. (Reihe: Woodhead Publishing India in textiles. New Delhi: Woodhead Publ. India, 2010, p. 272-289

Pelchen C., Schweiger C., Otter M. (Modeling and Simulating the Efficiency of Gearboxes and of Planetary Gearboxes), *Modeling and Simulating the Efficiency of Gearboxes and of Planetary Gearboxes*, 2002, p. 257-266

Pfund, T. (Electric Axle Drives – scalable propulsion system for electrified powertrains), *Electric Axle Drives – scalable propulsion system for electrified powertrains*, p. 1-16

Radzevich, S. P. (Dudley's handbook of practical gear design and manufacture): *Dudley's handbook of practical gear design and manufacture.* Second editioned. Boca Raton, London, New York, Ipswich, Massachusetts: CRC Press; EBSCO Industries, 2012

Ritari, A.; Vepsäläinen, J.; Kivekäs, K.; Tammi, K.; Laitinen, H. (Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes), *Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes*. In: Energies, Vol.13, 2020, 8, p. 2117

Rossi, C.; Pontara, D.; Falcomer, C.; Bertoldi, M.; Mandrioli, R. (A Hybrid–Electric Driveline for Agricultural Tractors Based on an e-CVT Power-Split Transmission), *A Hybrid–Electric Driveline for Agricultural Tractors Based on an e-CVT Power-Split Transmission*. In: Energies, Vol.14, 2021, 21, p. 6912

Schumacher, S.; Schmid, S.; Wieser, P.; Stetter, R.; Till, M. (Design, Simulation and Optimization of an Electrical Drive-Train), *Design, Simulation and Optimization of an Electrical Drive-Train*. In: Vehicles, Vol.3, 2021, 3, p. 390-405

Shen, Y.; Rinderknecht, S.; Hoppert, M. (General modelling method of power losses in transmission with parameter identification), *General modelling method of power losses in transmission with parameter identification*. In: Forsch Ingenieurwes, Vol.81, 2017, 2-3, p. 117-123

Tan, S.; Yang, J.; Zhao, X.; Hai, T.; Zhang, W. (Gear Ratio Optimization of a Multi-Speed Transmission for Electric Dump Truck Operating on the Structure Route), *Gear Ratio Optimization of a Multi-Speed Transmission for Electric Dump Truck Operating on the Structure Route*. In: Energies, Vol.11, 2018, 6, p. 1324

Verbruggen, F.; Rangarajan, V.; Hofman, T. (Powertrain design optimization for a battery electric heavy-duty truck), *Powertrain design optimization for a battery electric heavy-duty truck*: 2019 American Control Conference (ACC). 2019 American Control Conference (ACC), 7/10/2019 - 7/12/2019. [Place of publication not identified]: IEEE, 2019, p. 1488-1493

Verbruggen, F. J. R.; Silvas, E.; Hofman, T. (Electric Powertrain Topology Analysis and Design for Heavy-Duty Trucks), *Electric Powertrain Topology Analysis and Design for Heavy-Duty Trucks*. In: Energies, Vol.13, 2020, 10, p. 30

Wu, X.; Han, S.; Sun, H.; Han, G. (Efficiency analysis of planetary coupling drive system with dual motors on electric bus), *Efficiency analysis of planetary coupling drive system with dual motors on electric bus*: 2015 IEEE International Conference on Mechatronics and Automation (ICMA): *2 - 5 Aug. 2015, Beijing, China.* 2015 IEEE International Conference on Mechatronics and Automation (ICMA), 8/2/2015 - 8/5/2015. Piscataway NJ: IEEE, 2015, p. 2547-2552

Zdziennicki, Z.; Maciejczyk, A. (DESIGN BASIC OF INDUSTRIAL GEAR BOXES), *DESIGN BASIC OF INDUSTRIAL GEAR BOXES*, 2011

Zhang, Y.; Mi, C. (Automotive Power Transmission Systems):
Automotive Power Transmission Systems: Wiley, 2018