Summer 2023

JME 4110: Gearbox Design

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Joint Engineering Program

University of Missouri–St. Louis ▪ Washington University in St. Louis

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This team was tasked with designing or replacing an external gearbox for an electric-motor driven train car. A suitable replacement was sought for, but none was found; so, a complex set of gears, or compound gear train was designed. This gear train allowed for a smaller electric motor to drive the large rail car at appreciable speeds.

JME 4110 Mechanical Engineering Design Project

Gearbox Design

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1 INTRODUCTION

1.1 VALUE PROPOSITION / PROJECT SUGGESTION

This project required the design of a new gearbox system for Intramotev, a company developing battery operated automated railway vehicles to increase the efficiency, safety, and effectiveness of traditional rolling stock. Intramotive's current gearbox system does not comply with the Association of American Railroads (AAR) plat clearance requirements that dictates the boundary of all rails cars in the United States of America.

1.2 LIST OF TEAM MEMBERS

Brian Sniezak – Report Editor, Early Designs

Nick Drabb – Project Manager, Report Editor, Codes and Standards Research

Steven Nelson- Gear strength calculations, gear design, prototype modelling and printing

2 BACKGROUND INFORMATION STUDY

2.1 DESIGN BRIEF

The company Intramotev had electric boxcars where they attached external gearboxes for motor stepdown. Unfortunately, these gearboxes were too wide and conflicted with AAR standards. This team was tasked with either a) designing a new gear system, or b) finding an existing substitute, which fit within AAR parameters.

2.2 BACKGROUND SUMMARY

The initial project direction and design description was to design a planetary gearbox. The initial background research was of a couple of planetary gearbox systems for other applications that could help give insight and design direction into the use of a planetary gearbox for the application of driving a train car.

Automatic Transmission, How it works?

This is the automatic transmission created by Allison Transmission for high-end cars. While this transmission is for a car and not a train, it gives clear insight into how a planetary gearbox works at the fundamental level. It provides a good starting point for our design being for a vehicle, and what criteria and questions we need to address in designing ours.

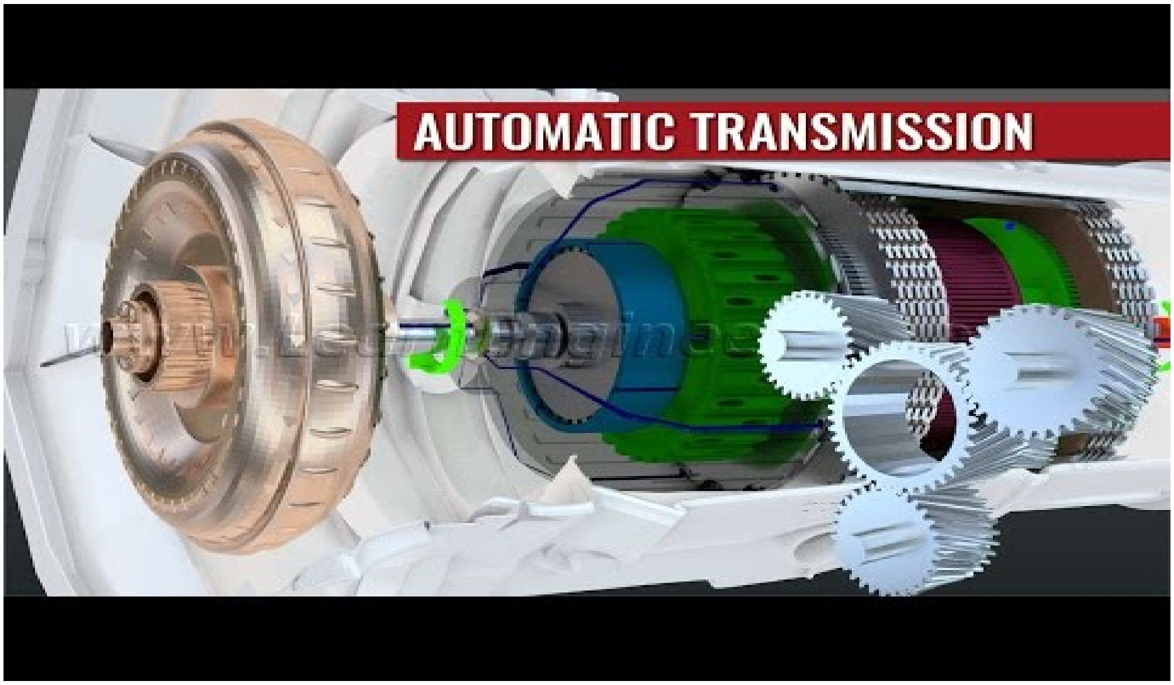

Figure 1: Automatic Transmission System

Jain, Pramod. Wind Energy Engineering. 2nd ed. New York: McGraw-Hill Education, 2016. https://www-accessengineeringlibrary-com.libproxy.wustl.edu/content/book/9780071843843.

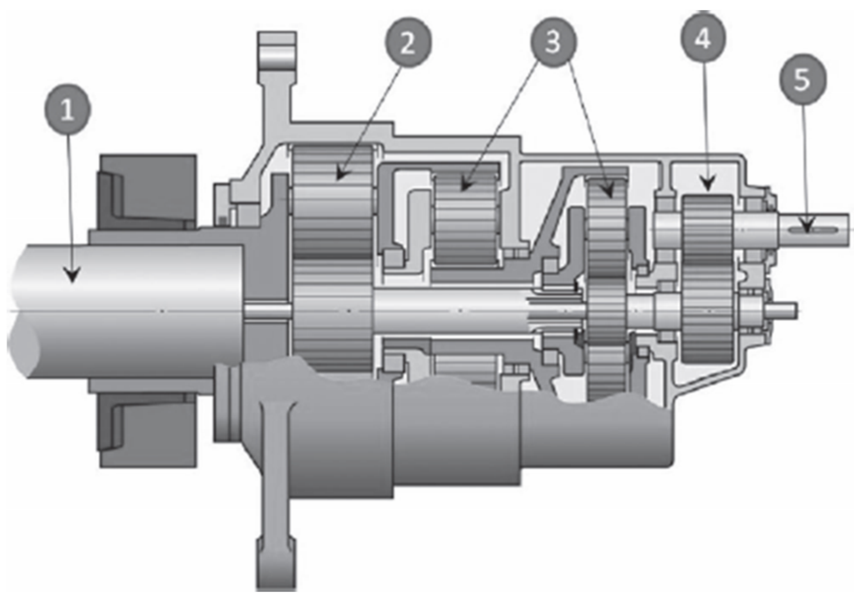

Figure 2: Wind Turbine Gearbox

This planetary gearbox is for a wind turbine, for changing the speed of shaft rotation to the generator. Reviewing gearboxes for different purposes exposes the similarities and differences between all gearboxes, revealing the qualities all gearboxes must have. For instance, the purpose of all gearboxes is to change the speed of a shaft, and this does so by connecting one set of planetary gears to another and then a third set.

There is also the gearbox that Intramotev is currently using. This is a planetary gearbox that meets many of the requirements for Intramotev. The crucial design requirement that is not met by this gearbox is the AAR plate clearance requirements.

https://www.apexdyna.com/AP_pro.aspx#

Figure 3: Current Gearbox

After some additional communication with Intramotev, it was determined that an offset gearbox should also be considered in addition to the original design direction of an inline planetary gearbox. Following is an example of an offset gearbox that exist that meets many of Intramotive's design requirements:

https://www.boschrexroth.com/en/us/company/press/gearboxes-electric-motors-rotatrac-egfz-2817.html

Similar to the currently used inline planetary gearbox, the "off the shelf" offset gearbox's that could be found that meet the design requirements fail to fit within the AAR plate clearance requirements.

Figure 4: Offset Gearbox

3 CONCEPT DESIGN AND SPECIFICATION

3.1 USER NEEDS AND METRICS

3.1.1 Record of the user needs interview

Table 1: User Needs

Need Number	Need	Importance
1	Neutral Gear	3
2	Torque Minimum 1,400	5
3	RPM Minimum 2,700	5
4	Runs at 55 MPH	5
5	Step down gear ratio 16:1	5
6	Direct axial line	3
7	Connects to Interface plates	5
8	Depth less than10" (Overall Performance Measure)	**5**
9	Reverse Gear	5
10	Easy to assemble	3
11	Easy to install	3
12	Gearbox Diameter	2
13	Step down gear ratio 8:1	1

3.1.2 List of identified metrics

Table 2: Identified Metrics for Gearbox

Metric Number	Associated Needs	Metric	Units	Minimum Value	Maximum Value
1	1	Depth	inches	6	10
2	2	Diameter	inches	10	32
3	3	Torque	Nm	2600	1400
4	4	Rotational Speed	rpm	3500	2700
5	5	Travel Speed	mph	55	1
6	6	Needed Gear Ratio	X:1	16	1
7	7	Wanted Gear Ratio	X:1	8	1
8	8	Neutral Gear	Binary	Yes	No
9	9	Direct Axial Line	Binary	Yes	No
10	10	Interface Connection	Binary	Yes	No
11	11	Reverse Gear	Binary	Yes	No
12	12	Easy Installation	Binary	Yes	No
13	13	Easy Assembly	Binary	Yes	No

3.1.3 Table/list of quantified needs equations

Table 3: Quantified Needs Equations

Inboard Motor Design		Metric															
		Depth	Diameter	Torque	Roational Speed	Travel Speed	Gear Ratio Need	Gear Ratio Want	Neutral Gear	Direct Axial Line	Interface connection	Reverse Gear	Easy Install	Easy Assembly	Need Happiness	Importance Weight	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Depth less than or equal to 10"	1													1	0.06	0.06
2	Gearbox Diameter		1												0.913043	0.1	0.091304
3	Torque Minimum 1,700 Nm			1											0.250624	0.1	0.025062
4	RPM Minimum 2,700 RPM				1										0.001248	0.1	0.000125
5	Runs at 55 MPH					1									1	0.1	0.1
6	Step down gear ratio 16:1						1								1	0.06	0.06
7	Step down gear ratio 8:1							1							0	0.1	0
8	Neutral Gear								1						0	0.1	0
9	Direct axel line									1					0	0.1	0
10	Connects to interface plates										1				1	0.06	0.06
11	Reverse Gear											1			1	0.06	0.06
12	Easy to install												1		0	0.04	0
13	Easy to assemble													1	0	0.02	0
Units		inches	inches	Nm	RPM	MPH	Ratio (X:1)	Ratio (X:1)	Binary	Unit 9	Unit 10	Unit 11	Unit 12	Unit 13	Total Happiness		0.456492
Best Value		6	10	2600	3500	55	16	8	1	1	1	1	1	1			
Worst Value		10	32	1400	2700	1	1	1	0	0	0	0	0	0			
Actual Value		6	12	1700	2700	55	16	0	0	0	1	1	0	0			
Normalized Metric Happiness		1	0.913043	0.250624	0.001248	1	1	0	0	0	1	1	0	0			

3.2 CONCEPT DRAWINGS

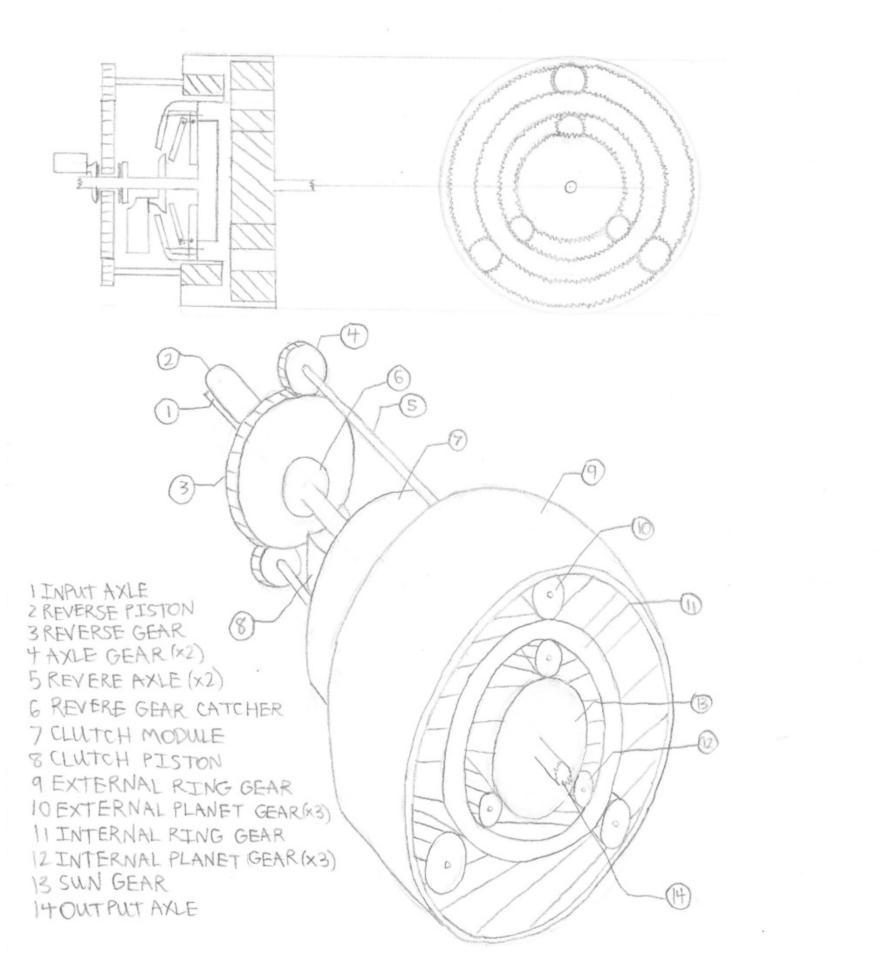

Figure 5: In-Line Planetary

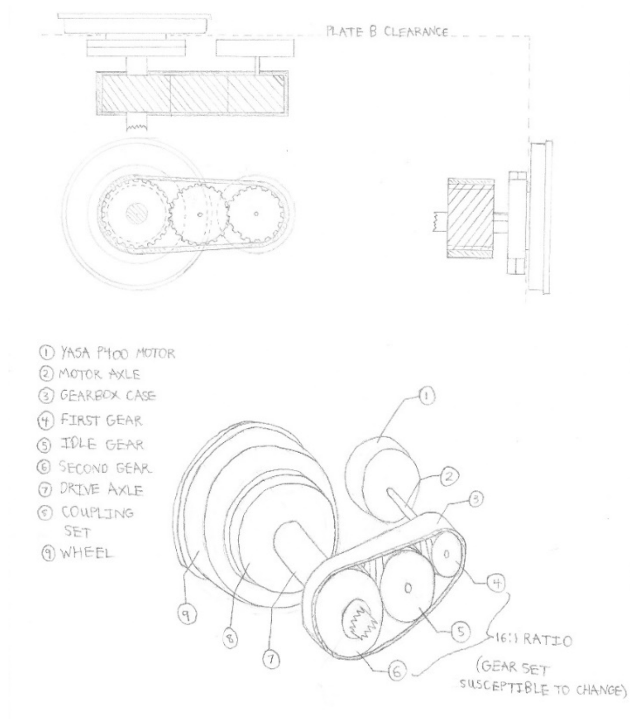

Figure 6: Single Stage Coplanar

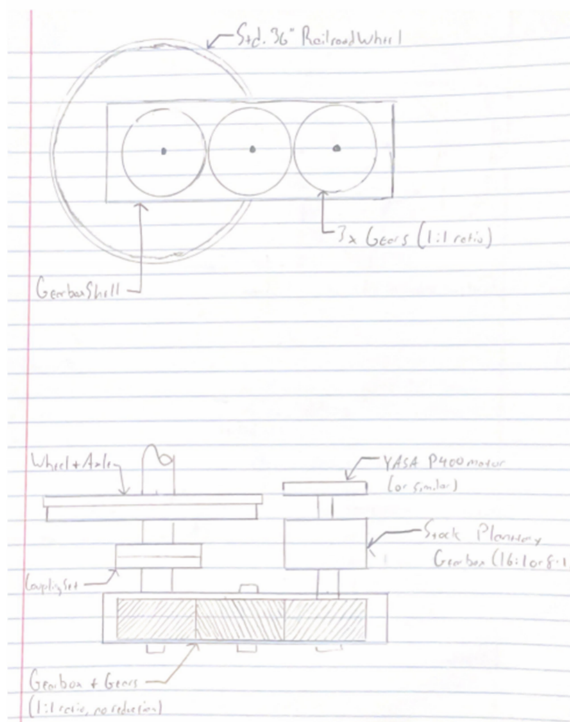

Figure 7: Parallel Gearset with Inboard Planetary

3.3 CONCEPT SELECTION PROCESS

3.3.1 Concept scoring

In-Line Planetary Inboard Motor Design		Metric															
		Metric 1 (Depth -Inches)	Metric 2 (Diameter - Inches)	Metric 3 (Torque - Nm)	Metric 4 (RPM)	Metric 5 (Speed - MPH)	Metric 6 (Gear Ratio Need - Ratio)	Metric 7 (Gear Ratio Want - Ratio)	Metric 8 (Yes/No - Neutral gear)	Metric 9 (Yes/No - indirect axial line)	Metric 10 (Yes/No - Interface connection)	Metric 11 (Yes/No - Reverse Gear)	Metric 12 (Yes/No - Easy Install)	Metric 13 (Yes/No - Easy Assemble)	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Depth less than or equal to 10"	1													0.8	0.06	0.048
2	Gearbox Diameter		1												0.782609	0.1	0.078261
3	Torque Minimum 1,700 Nm			1											1	0.1	0.1
4	RPM Minimum 2,700 RPM				1										0.37578	0.1	0.037578
5	Runs at 55 MPH					1									1	0.1	0.1
6	Step down gear ratio 16:1						1								1	0.06	0.06
7	Step down gear ratio 8:1							1							0.125	0.1	0.0125
8	Neutral Gear								1						1	0.1	0.1
9	Direct axel line									1					1	0.1	0.1
10	Connects to interface plates										1				1	0.06	0.06
11	Reverse Gear											1			1	0.06	0.06
12	Easy to install												1		1	0.04	0.04
13	Easy to assemble													1	1	0.02	0.02
Units		inches	inches	Nm	RPM	MPH	Ratio (X:1)	Ratio (X:1)	Binary	Unit 9	Unit 10	Unit 11	Unit 12	Unit 13	Total Happiness		0.816339
Best Value		6	10	2600	3500	55	16	8	1	1	1	1	1	1			
Worst Value		10	32	1400	2700	1	1	1	0	0	0	0	0	0			
Actual Value		7	15	2600	3000	55	16	1	1	1	1	1	1	1			
Normalized Metric Happiness		0.8	0.782609	1	0.37578	1	1	0.125	1	1	1	1	1	1			

Figure 8: Design One Score

Single Stage Coplanar		Metric															
		Metric 1 (Depth -Inches)	Metric 2 (Diameter - Inches)	Metric 3 (Torque - Nm)	Metric 4 (RPM)	Metric 5 (Speed - MPH)	Metric 6 (Gear Ratio Need - Ratio)	Metric 7 (Gear Ratio Want - Ratio)	Metric 8 (Yes/No - Neutral gear)	Metric 9 (Yes/No - direct axial line)	Metric 10 (Yes/No - Interface connection)	Metric 11 (Yes/No - Reverse Gear)	Metric 12 (Yes/No - Easy Install)	Metric 13 (Yes/No - Easy Assemble)	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Depth less than or equal to 10"	1													0.6	0.06	0.036
2	Gearbox Diameter		1												0.652174	0.1	0.065217
3	Torque Minimum 1,700 Nm			1											0.250624	0.1	0.025062
4	RPM Minimum 2,700 RPM				1										1	0.1	0.1
5	Runs at 55 MPH					1									1	0.1	0.1
6	Step down gear ratio 16:1						1								1	0.06	0.06
7	Step down gear ratio 8:1							1							0	0.1	0
8	Neutral Gear								1						0	0.1	0
9	Direct axel line									1					0	0.1	0
10	Connects to interface plates										1				1	0.06	0.06
11	Reverse Gear											1			0	0.06	0
12	Easy to install												1		1	0.04	0.04
13	Easy to assemble													1	1	0.02	0.02
Units		inches	inches	Nm	RPM	MPH	Ratio (X:1)	Ratio (X:1)	Binary	Unit 9	Unit 10	Unit 11	Unit 12	Unit 13	Total Happiness		0.50628
Best Value		6	10	2600	3500	55	16	8	1	1	1	1	1	1			
Worst Value		10	32	1400	2700	1	1	1	0	0	0	0	0	0			
Actual Value		8	18	1700	3500	55	16	0	0	0	1	0	1	1			
Normalized Metric Happiness		0.6	0.652174	0.250624	1	1	1	0	0	0	1	0	1	1			

Figure 9: Design Two Score

		Metric															
Parallel Gearset with Inboard Planetary		Metric 1 (Depth -Inches)	Metric 2 (Diameter - Inches)	Metric 3 (Torque - Nm)	Metric 4 (RPM)	Metric 5 (Speed - MPH)	Metric 6 (Gear Ratio Need - Ratio)	Metric 7 (Gear Ratio Want - Ratio)	Metric 8 (Yes/No - Neutral gear)	Metric 9 (Yes/No - direct axial line)	Metric 10 (Yes/No - Interface connection)	Metric 11 (Yes/No - Reverse Gear)	Metric 12 (Yes/No - Easy Install)	Metric 13 (Yes/No - Easy Assemble)	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
Need#	Need	1	2	3	4	5	6	7	8	9	10	11	12	13			
1	Depth less than or equal to 10"	1													0.8	0.06	0.048
2	Gearbox Diameter		1												0.5	0.1	0.05
3	Torque Minimum 1,700 Nm			1											1	0.1	0.1
4	RPM Minimum 2,700 RPM				1										0.875156	0.1	0.087516
5	Runs at 55 MPH					1									1	0.1	0.1
6	Step down gear ratio 16:1						1								1	0.06	0.06
7	Step down gear ratio 8:1							1							0	0.1	0
8	Neutral Gear								1						0	0.1	0
9	Direct axel line									1					0	0.1	0
10	Connects to interface plates										1				1	0.06	0.06
11	Reverse Gear											1			1	0.06	0.06
12	Easy to install												1		0	0.04	0
13	Easy to assemble													1	0	0.02	0
Units		inches	inches	Nm	RPM	MPH	Ratio (X:1)	Ratio (X:1)	Binary	Unit 9	Unit 10	Unit 11	Unit 12	Unit 13	Total Happiness		0.565516
Best Value		6	10	2600	3500	55	16	8	1	1	1	1	1	1			
Worst Value		10	32	1400	2700	1	1	1	0	0	0	0	0	0			
Actual Value		7	21.5	2600	3400	55	16	0	0	0	1	1	0	0			
Normalized Metric Happiness		0.8	0.5	1	0.875156	1	1	0	0	0	1	1	0	0			

Figure 10: Design Three Score

3.3.2 Preliminary analysis of each concept's physical feasibility

Design One: In-Line Planetary

This design most closely follows the original criteria given by Intramotev. It has a clutch that supplies a neutral gear and a planetary system for the stepdown. It is, however, the most complex design, and time may not allow for its completion.

Design Two: Single Stage Coplanar

This is the simplest of the designs due to the coplanar gears providing the stepdown directly from the motor to the wheel. However, for the gears to do something like that, the gears diameters will have to be exceptionally large: maybe too large for the constraints.

Design Three: Parallel Gearset with Inboard Planetary

This design utilizes both a planetary gearset and a simple gear train. The planetary set provides the stepdown, and the simple train transmits it to the wheel and axle. Since it combines two different gear sets together, it is quite complicated; the gear sets are side by side, so it will also be thicker than other designs.

3.3.3 Final summary statement

We abandoned the planetary design due to time constraints and advice from Intramotev. We also went with the off-axial method so we could meet the depth parameter. We were then split between the simple or the compound gear train and took time to explore each design. In our preliminary calculations, the simple gear train failed to meet the radius constraint, so we settled on the compound design.

3.4 PROPOSED PERFORMANCE MEASURES FOR THE DESIGN

The single most important user need for this project would be the depth of the gearbox. The depth of the gearbox design ties directly to Standard S-2056: Clearance Plate Diagrams for Interchange Service. This standard is gone over in greater detail in the Codes and Standards portion of this report, Section 7. This standard dictates the outer boundary that all rail cars of a specific type must comply with to safely travel on rail ways in the United States of America. The current design being utilized by Intramotev exceeds the Plate B boundary and can therefore only travel on private railways for demonstrations.

3.5 REVISION OF SPECIFICATIONS AFTER CONCEPT SELECTION

After we had run our first set of designs through the "needs equations" and decided on a design we thought would best meet the client needs, we received updated parameters and direction from Intramotev. Our initial client need was to have an inline planetary gearbox system. This was what we focused our early design ideas off of. We later had a follow-up discussion with a different representative of the client who proposed a new direction. As indicated in the final summary statement above (Section 3.3.3), due to time constraints and depth constrains, Intramotev proposed that we look at off the shelf alternatives to the current off the shelf gearbox being utilized or to look at an off-axial gearbox design. When provided with these updated parameters, our team decided to address both options at once to stay on track with time.

We looked into several off the shelf gearboxes to try and find one that would meet Intramotive's requirements relating to RPM capabilities (2,700 to 3,500), torque limits (1,400 Nm to 2,600 Nm), diameter (32" maximum) and depth (10" maximum). Taking all of this into account there were several options found that met some of the requirements. One of the more promising results was an offset gearbox for electric motors from Bosch Rexroth. Unfortunately, this product, like most found, did not comply with the most crucial depth parameter and therefore was not a valid option.

At the same time as researching off the shelf options, revisions to the design continued with a focus on an off-axial gearbox design. This ultimately led to a compound geartrain. With what became our final design, it met all the requirements set forth by Intramotev. Most importantly the off-axial design met the depth requirements. These are the revisions that led to what became our final design.

4 EMBODIMENT AND FABRICATION PLAN

4.1 EMBODIMENT/ASSEMBLY DRAWING

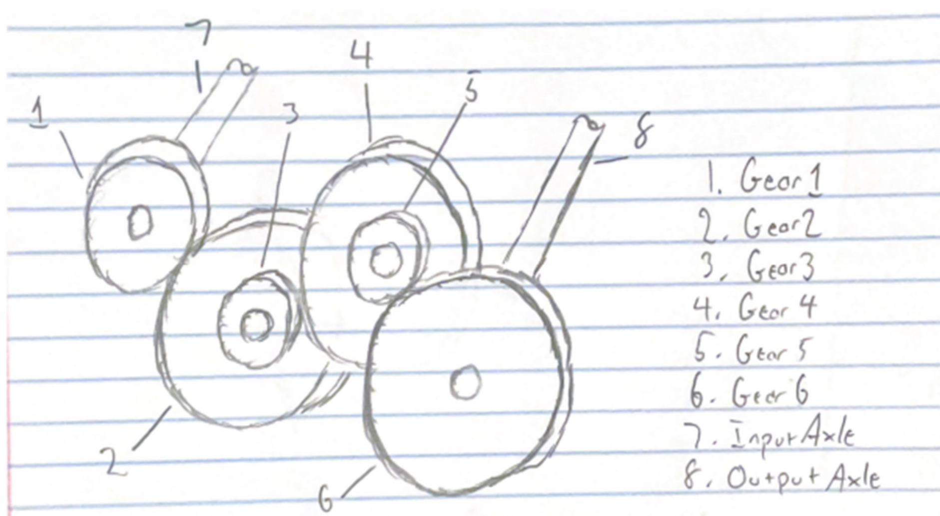

Figure 11: Initial Embodiment Drawing

4.2 PARTS LIST

Table 4: Parts List

1	Gear 1
2	Gear 2
3	Gear 3
4	Gear 4
5	Gear 5
6	Gear 6
7	Input Axle
8	Output Axle

4.3 DRAFT DETAIL DRAWINGS FOR EACH MANUFACTURED PART

See appendix for full engineering drawings.

4.4 DESCRIPTION OF THE DESIGN RATIONALE

During the initial design process, much of the part design was driven by the limited requirements provided by the sponsor, so the parts required to be designed were fewer than seen in the embodiment drawing. The only portions required by the team are the First Gear, the Idle Gear, and the Second Gear, with the other components to be designed by the sponsor to meet their physical space limitations.

The most important factor during the initial design process is the gear ratio. With a target ratio of 16 input turns to 1 output turn, the team varied the number of teeth to get as close as possible to the required ratio. This then became the basis for changing the gear module, or general tooth size, to get the outer diameter of the largest gear as close to, but less than, the maximum size requirement of the gearbox.

5 ENGINEERING ANALYSIS

5.1 ENGINEERING ANALYSIS PROPOSAL

5.1.1 Signed Engineering Analysis Contract

MEMS 411 / JME 4110

MECHANICAL ENGINEERING DESIGN PROJECT

ASSIGNMENT 5: Engineering analysis task agreement

ANALYSIS TASKS AGREEMENT

PROJECT: Rail Gearbox NAMES: Nick Drabb
Steven Nelson
Brian Sniezak

INSTRUCTOR: Craig Geismann
Mark Jakiela

The following engineering analysis tasks will be performed:

- Pre-selection ideal calculations, to include gear ratio calculations and torque values
- Gear calculations to match practical application and performance requirements based on gear depth and speeds, along with other gear profile modifications
- Match modeled gear set to fit within rail clearance specifications per rail standards
- Create 3D model of gear set to ensure proper meshing and overall dimensions, minus containment box (to be designed by customer)
- Create 2D model of gear train versus railcar bogey to compare clearances with final gear assembly

The work will be divided among the group members in the following way:

Nick: 2D modeling and plate clearance confirmations

Steven: 3D gear modeling and tooth profile calculations

Brian: preliminary ratio calculations, pre-selection calculations

7-28-2023

7-31-2023

Figure 12: Engineering Analysis Agreement

5.2 ENGINEERING ANALYSIS RESULTS

5.2.1 Motivation

Analysis on the general gear train parameters must be done in order to ensure the gear train can not only perform at the required input and output torque values, but also the input and output speeds.

5.2.2 SUMMARY STATEMENT OF ANALYSIS DONE

The initial engineering analysis involved determining the most effective gear interaction to achieve the required torque and overall size of the final system. First, hand calculations were performed to determine the required number of teeth on each gear to get as close as possible to a 16:1 gear ratio. A simple/coplanar gear train was quickly ruled out due to the large difference between gear tooth numbers, so the decision was made to move to a complex gear train, with two gears sharing a single axle.

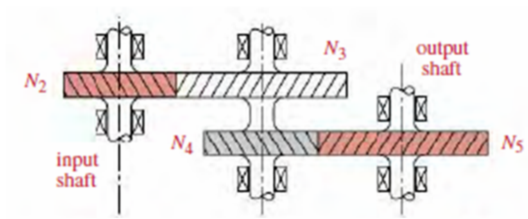

Figure 13: Simplified Complex Gear Train

After tooth counts were determined, the gear module was then modified to keep the output gear's outer diameter within the sponsor provided overall height of 18". The module is the ratio of gear pitch diameter to number of teeth, and directly affects the size and strength of a gear.

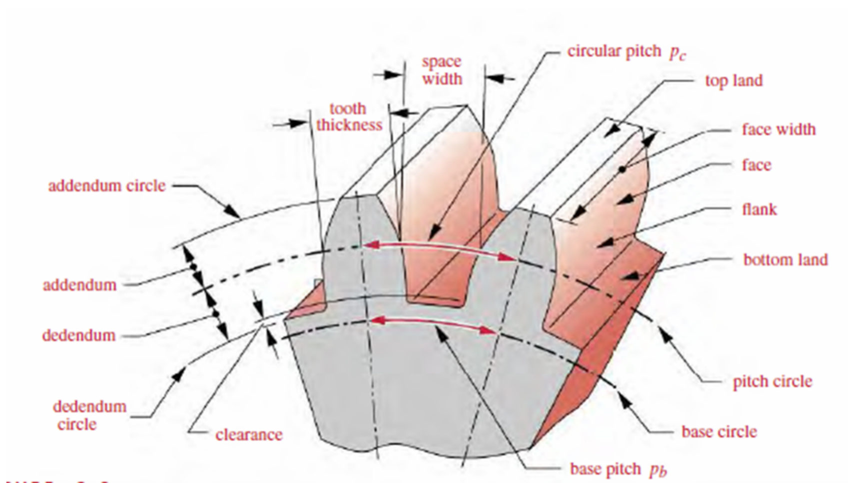

Figure 14: Gear Design Nomenclature

The bulk of the engineering analysis done was to ensure the final gear design could handle the stepped-up torque and shear forces of the system. A 16:1 gear train will take the 790 nm of torque output generated by the YASA 750R electric motor and output nearly 13,000 nm of torque. The engineering design calculations were performed with a built-in safety factor, with an input torque of 1000 nm. Once tooth count and module were determined, the gear thickness was then varied to meet each gear's torque requirement.

Calculations were performed for each gear mesh interaction to ensure capabilities at each stage. These were done though Excel's formula functions, which allowed for quick changes between different parameters. The calculations for gear force were done using the formulas below to find gear face forces and to determine the bending force of the individual teeth.

5.2.3 Methodology

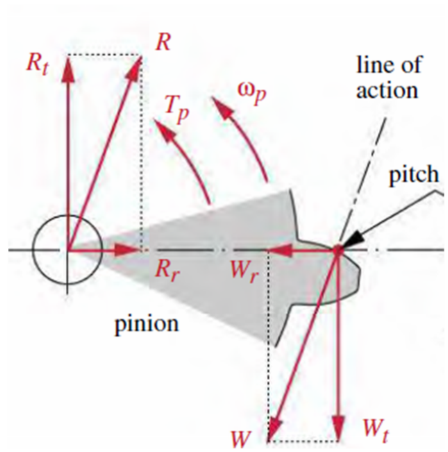

Figure 15: Gear Forces

In order to calculate the forces acting within a gear, the forces at work must be calculated. The tangent force is a function of the gear torque and the pitch diameter of the gear and can be found using the below equation.

$$W_{tangent} = \frac{Gear\ Torque}{Pitch\ Diameter}(Newtons)$$

Figure 16: Gear Tooth Tangent Torque

Once the tangent force is found, bending stress can be determined with the formula below.

$$\sigma_b = \frac{W_t}{FmJ} \cdot K$$

Figure 17: Bending Stress Formula

In this formula, F represents the face width of the gear in mm, m represents the module, and J is a tabulated bending factor. This table value uses the gear pressure angle and the helix angle of the gear to determine the bending force of the tooth. A gear pressure angle of 25° and a helix angle of 35° were used in these gears, producing a J factor of 0.58. This formula also uses the K factor. This is a combination of an application/shock factor, a rim bending factor, an idler factor, load distribution factor, a size factor, and a velocity factor. For the gears in this application, a K overestimation of 2.1 was used.

The material SCM 435 was decided upon as a high-strength, chromium-molybdenum, low-carbon steel. This is a Japanese steel used by Japanese manufacturer KHK Gears, whose online calculator was used to verify our calculations. The goal of this calculation was to keep the total bending force below 1/3 of the yield strength of the material. The yield strength of SCM 435 is 930 MPa.

5.2.4 Results

These calculations drove the entire design of the gear train. The final design parameters for this gear train can be seen below.

Table 5: Gear Dimensions

Gear No.	Teeth	Thickness (mm)	Module	Pressure Angle	Bending (MPa)
1	10	40	8	25	158.83
2	27	40	8	25	158.83
3	12	60	8	25	238.24
4	35	60	8	25	238.24
5	13	80	12	25	213.81
6	23	80	12	25	213.81

5.2.5 Significance

An Excel-based calculator was set up to speed up the decision-making process. To keep within the 18" outer diameter and the 10" maximum depth of the gear train, the gear modules and thickness were balanced until the gear train dimensions met the requirements of the sponsor. These dimensions were based almost entirely on meeting the maximum input torque for the system; changes to the K factor may be required should the input speed be increased beyond that of the YASA 750R motor maximum.

6 RISK ASSESSMENT

6.1 RISK IDENTIFICATION

Risk is an uncertain event or condition that if it occurs, has a positive or negative effect on project objectives [1]. With any project, risk identification is one of the most crucial steps when starting your risk management process. Identifying major risks can help point out potential issues as well as provide solutions to any identified risks. Identifying these risks will help mitigate any negative impacts that arise if any of these issues should happen. With that in mind, our team came up with eight (8) potential risks:

1. Gearbox Fails
2. Gearbox Gets Damaged
3. Motor Manufacturer Adjust its equipment
4. Motor Fails
5. Train Bolting pattern on axel is different
6. The Motor Changes
7. Gear manufacturer goes out of business
8. Client wants different gear ratio

We came up with these risks first thought of equipment failure due to wear and tear or due to site conditions. After that, we thought about potential changes in equipment, dimensions, manufacturers, and even client requested updates.

6.2 RISK ANALYSIS

In analyzing the risks, we discussed the potential impact each of the risks could have on our project. The following is a more detailed explanation of the effect the risks listed above could have on our project.

1. Gearbox Fails: If the gear box were to fail, that train car, potential multiple train cars, would be out of service while the gearbox is repaired and or replaced. This could have an impact on train schedules and even costs in contracts due to late delivery.
2. Gearbox Gets Damaged: This could range from a minor fix to a major fix. This was more related to site conditions, such as a branch or fallen stone that is laying in the plate clearance and strikes the gear box. This could impact train delivery schedules while the gearbox is repaired.
3. Motor Manufacturer Adjust its equipment: Adjusted dimensions of motor used could impact interface plates between motor and gearbox. Now if the motor is adjusted, this would most likely mean the train would be out of service already for updates. However, there would mostly likely be a cost incurred to have a new interface plate that goes between the motor and gearbox manufactured
4. Motor Fails: If the motor fails, the gearbox will need to be removed to be able to access and repair and/or replace the motor. This will potentially impact schedules and even revenue depending on how long repairs take. While mounting equipment would be Intramotive's responsibility, it would be recommended that the gearbox be installed in such a way to allow for easy removal for quicker motor access.
5. Train Bolting pattern on axel is different: While most train axel bolting patterns are the same, not all of them are. Also, there are potential differences with international trains. Ideally these differences would be known prior to installation. However, it may require the special order of a new interface plate between the gearbox and train axel. This could delay the start-up of the new self-driving train system for that client.
6. Motor Changes: Motor change could potentially have several impacts. Ideally there will be little to no difference and worse case is removing the gearbox to be able to install the new motor. However, a new motor could require a different interface between the motor and the gearbox. A new motor's specifications could exceed the gearbox's capabilities, requiring a potential redesign of the gearbox system.
7. Gear manufacturer goes out of business: This could result in having to find a new client to produce new gearboxes and/or gear replacement parts. This would ideally happen when service on a train is not required and would not have an impact on any train schedules.   However, this could cause delays if this happens during the need for a repair or replacement, potentially causing a client time and money.
8. Client wants different gear ratio: Depending on how severe the change, this could potentially be an entire redesign.

6.3 RISK PRIORITIZATION

The risks below were prioritized by failures more specifically related to the gearbox itself. After that, risks were related to components interacting with the gearbox. Finally risks coming from an item such as client changes were considered.

Table 6: Risk Register

Risk Management Register

0	Open Red Risks
2	Open Yellow Risks
4	Open Green Risks
0	Risks w/ no Response Strategy
0	Closed risks

Project Name: Intramotive Gearbox
Project Manager: Nick Drabb
Start Date: 7/24/2023

Location: Washington University
Add'l Info:
Updated On: 8/14/2023
Overall Project Risk Indicator: #DIV/0!

Risk Level

Probability					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
Impact	1	2	3	4	5

Legend:

Impact
1 - Negligible
2 - Marginal
3 - Significant
4 - Critical

Probability
1 - Rare
2 - Unlikely
3 - Possible
4 - Likely

Item	Project/ Phase	Risk Status	Risk	Potential Impact (Cause and Effect)	Risk Response Strategy	Triggers (Indicators that the risk will occur)	Estimated Schedule Impact (Days)	Maximum Exposure ($000)	Estimated Exposure (Contingency) ($000) $0	Risk Category	Risk Sub Category	Action Owner	Start Exposure	End Exposure	Baseline Risk Scoring: Impact: Tech Perf	Schedule	Cost	Safety	Probability	Risk Ranking
1		Open	Gearbox Fails	The train will be out of commision while gearbox is replaced or new is ordered.	Intramotive to have stock of several full gearboxes as well as replacment parts to allow for minimal down time.	Regular maintanence would ideally provide warning of any major gearbox failure coming.		$9,233		Performance		Intramotive				5	4		3	15
2		Open	Gearbox gets Damaged	this could range from minor fix in the field to a full replacement.	Intramotive to have stock of several full gearboxes as well as replacment parts to allow for minimal down time.	Regular maintanence would ideally provide warning of any major gearbox failure coming. However damage could happen due to unavoidable site condtions.		$9,233		Performance		Client				1	1	1	4	4
3		Open	Motor Manufacturer Adjust its Equipment	Adjusted dimensions of motor used could impact interface plates or other connected equipment.	Prepair to have crucial interface components ready for adjustment. Potentially have additional interface plates made to match several industry standard motor interface bolt patterns.	Keeping good relationships and constant contact with manufacturer in order to find out of any potential future changes to equipment.		$1,200		Performance		Intramotive				1			5	5
4		Open	Motor Goes Out	If the motor goes out, the gearbox will need to be removed to be able to access the motor.	Get service mechanic to train car in question as soon as possible. Intramotive responsible for design of mounting system which will allow for easy removal of gearbox to be able to access the motor.	Performance of motor starts to suffer. Recommend regular maintance and monitoring. This will allow to potentially forsee motor failure and possibly make repairs during optimal down time in serivce.		$1,000		Performance		Intramotive				2	2		4	8
5		Open	Train bolting patterin on axel is different	roughly 85% of trains have same axel pattern, but some trains will have a different bolting pattern, requireing a different bolt pattern.	Have at least drawings ready for serveral "next it line" most comon axel bolting patterns. This will minimize time needed to provide new interface plate.	When working with a new client, a discussion would be had to verify the exact bolting patter for the trains to be modified		$1,200		Construction		Intramotive/ Client				3			3	9
6		Open	The Motor Changes	There is an interface plate between the motor and the gearbox. A new plate may be needed of the motor changes. This could also impact the gear ratio of the gearbox	Verify exact motor specification immediately to see if existing gearbox is capible of handling new motor power, RPM, etc.	If this change comes from Intramotive, it would be verified that the existing gearbox is adequate or a new gearbox would be in design prior to getting new morot. If Client makes change, then impact on schedule will need to be discussed.				Technology		Intramotive/ Client				1			5	5
7		Open	Gear Manufacturer Goes Out of Business	Equipment interfaces and gear ratios are associated with the equipment selected. This is only a risk of an off the shelf piece of equipment is used.	A new manufacturer will need to be contacted to be able to produce new gearboxes and or replacment parts. When obtaining bids for contract, keep 2nd and 3rd place bids for backups or alternates	Keeping constant contact will manufacturer will hopefully allow updates on company status. However, a company going out of business could happen without notice.				Schedule		Intramotive				2	2		1	2
8		Open	Cleitn Wants different gear Ratio	The gearbox is setup for one ratio. A new gearbox may need ot be designed to work with a different gear ratio	The response would be to veriy client understands potential impact as this may require a new gearbox/design. This would be a huge impact to schedule and have a high cost	This is something that would not be recommended and the all other avenues would be exhausted if a client made this request.				Technology		Client				5	5		1	5

7 CODES AND STANDARDS

7.1 IDENTIFICATION

There were several codes and standards that had an impact on our design and design process. Before going into a couple of code sections that impacted this project there were a couple of standards that needed to be mentioned. These standards required additional funding for purchase and should be considered:

IEC 60349-1:2010: Electric traction – Rotating electrical machines for rail and road vehicles. This standard is applicable to rotating electrical machines, other than electronic converter-fed alternating current motors, forming part of the equipment of electrically propelled rail and road vehicles. The vehicles may obtain power either from an external supply or from an internal source. The object of this standard is to enable the performance of a machine to be confirmed by tests and to provide a basis for assessment of its suitability for a specified duty and for comparison with other machines.

IEC 61800-1:2021: Adjustable speed electrical power drive systems. This standard applies to adjustable speed electric DC power drive systems, which include semiconductor power conversion and the means for their control, protection, monitoring, measurement and the DC motors. It applies to adjustable speed electric power drive systems intended to feed DC motors from a BDM/CDM connected to line-to-line voltages up to and including 1 kV AC 50 Hz or 60 Hz and/or voltages up to and including 1,5 kV DC input side.

There are two standards that will be discussed in greater detail that played a part in the design of this project:

ISO 9001 – Quality management systems – Requirements

Standard S-2056 Clearance plate diagrams for interchange service

7.2 JUSTIFICATION

ISO 9001 – Quality management systems – Requirements

ISO 9001 could (and probably should) apply to just about any service or product where there is a client involved. It was determined that this standard would have a relevancy to this project due to the level of communication involved along with the unique nature of the project. With the custom nature of this project, designing a custom gearbox, it is crucial (even a constraint) to provide a consistent product that meets the customer's needs and requirements. This standard helps lay the foundation to have a quality management system in place to help deliver that consistent product. From the leadership level, planning and support, design and development, improvement, and evaluation, ISO 90001 helps layout all these levels. This standard echoes MANY procedures and practices laid out in this class and are extremely crucial to deliver a satisfactory product to our client.

Standard S-2056 Clearance plate diagrams for interchange service

This standard, S-2056, has one of the largest impacts on this entire project. For our project, designing a gearbox that can get the power from the motor to the train wheels has many aspects to it. Determining the best gear ratio to get the RPM from the electric motor to an acceptable RPM for the train wheel, a gearbox that can handle the torque output from the electrical motor, and the interface between motor and gearbox and train axel, are all design aspects of this project. All these aspects MUST fit into the plate clearance governed by standard S-2056 put forth by the AAR. Meeting the requirements of the plate B clearance indicated in standard S-2056 is the highest importance of the entire project.

7.3 DESIGN CONSTRAINTS

ISO 9001 – Quality management systems – Requirements

The ISO 9001 Quality management system creates constraints in the method of how a project is handled. It keeps a project on a specific track, constraining it to one style of quality management, helping to avoid a poorly run project. The constraints of the quality management system impact all aspects of the project from leadership to design and even the ways to interact with clients. Constraining a project management system to the track laid out in the ISO 9001 standard will allow a team to focus on the client and project at hand instead of trying a potentially scattered and disjointed management system.

Standard S-2056 Clearance plate diagrams for interchange service

In Standard S-2056, the client Intramotev has informed us that the train cars they will be using fall under the requirements of Plate B. See Figure 1 for reference. The dimensions shown indicate the overall dimensional constraints that all train carts governed by "Plate B" must comply with. Train tracks across the United States are designed to allow safe passage of trains designed to these standards. If there are parts of the train that fall outside of these dimensions, then safety will be compromised. Equipment such as the gearbox could be damaged, or someone could get hurt.

7.3.1 Functional

The gearbox must operate at a high level for extended periods of time, with little to no maintenance required. This requirement plays a large part in the design and production of the gears and mating components. The function of the gearbox must be near perfect to make the financial and engineering case worth the time and effort required.

7.3.2 Manufacturing

One of the more difficult constraints in this project is the manufacturing of the components. As the gearbox and individual gears are not readily available, custom manufacturers must be utilized to have the parts made to the required dimensions, surface finish, and hardnesses required. Additionally, the casing must be custom manufactured until a casting profile can be designed for long-term production, increasing the cost and difficulty of manufacturing.

7.4 SIGNIFICANCE

ISO 9001 – Quality management systems – Requirements

The final prototype will be impacted because the whole process of the design is, in some way, controlled by the ISO 9001 Quality Management system. Dimensions, material choices, or construction methods may not be directly affected by this standard, but the process laid out by this standard will help decide the best way to come to a decision with the client on dimensions, materials, and construction methods.

Standard S-2056 Clearance plate diagrams for interchange service

This will have the largest impact on our design. Needing to stay within plate B clearance requirements is what drove Intramotev to propose this as a design problem. This has created a dimension constraint on our entire project. The entire body of our gearbox must be able to attach to the train axle all while still fitting into the "Plate B" required dimensions. This has an impact on design, material chosen, and layout (inline or offset). The dimensions we are constrained to will be shown in our final documentation drawing.

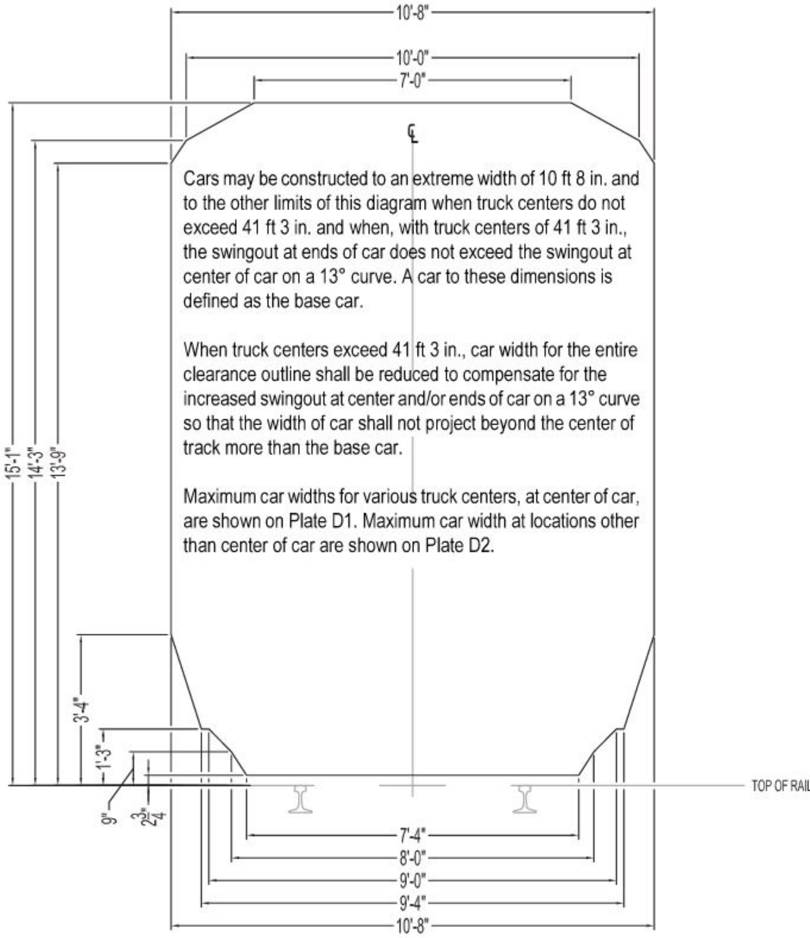

Figure 18: Plate B Clearance Dimensions

8 WORKING PROTOTYPE

8.1 PROTOTYPE PHOTOS

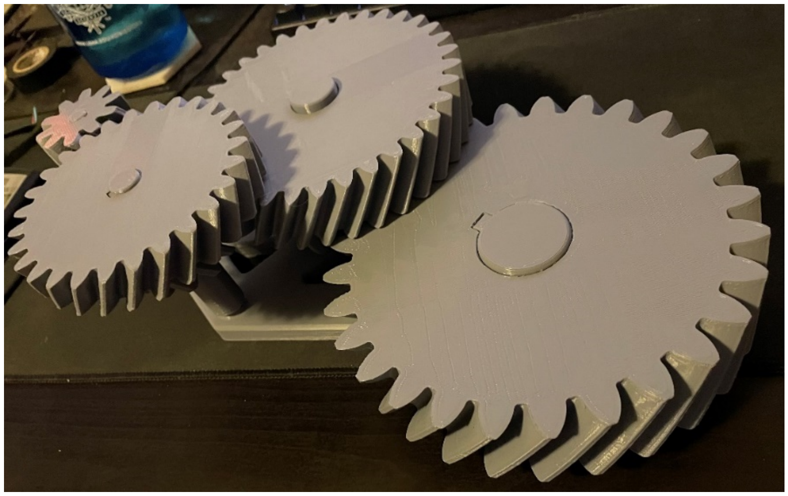

Figure 19: Half-Scale Printed Gear Set

Figure 20: Half-Scale 3D Printed Gear Set Overhead

8.2 WORKING PROTOTYPE VIDEO

A video clip showing the approximate geartrain and rail car interaction can be seen in the link below:
https://youtu.be/5Zz4-2LTvYg

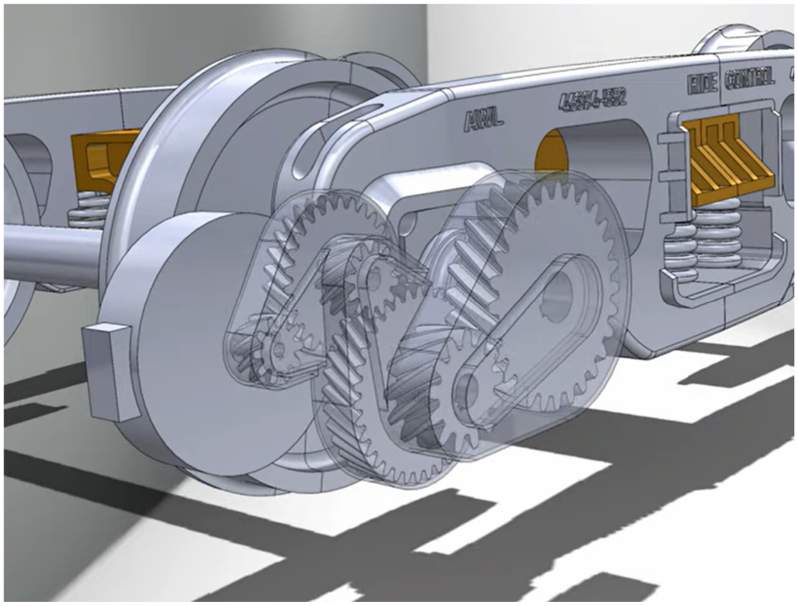

Figure 21: Prototype Video

8.3 PROTOTYPE COMPONENTS

To better visualize the gear interactions, a mockup base was designed and printed with the gears at 50% scale. These allowed the team to better understand the gear profiles and the scale of the parts being designed. The below image displays the gears with the mockup base and temporary axles.

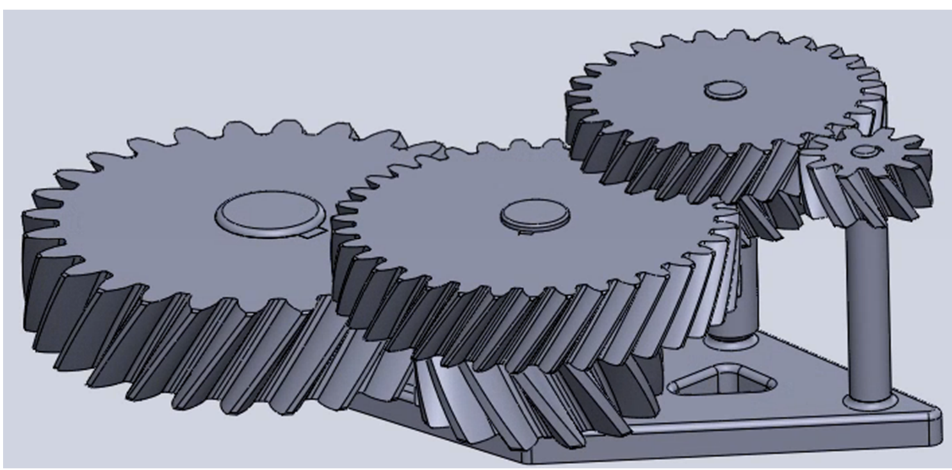

Figure 22: Modelled Gears on Mockup Base and Axles

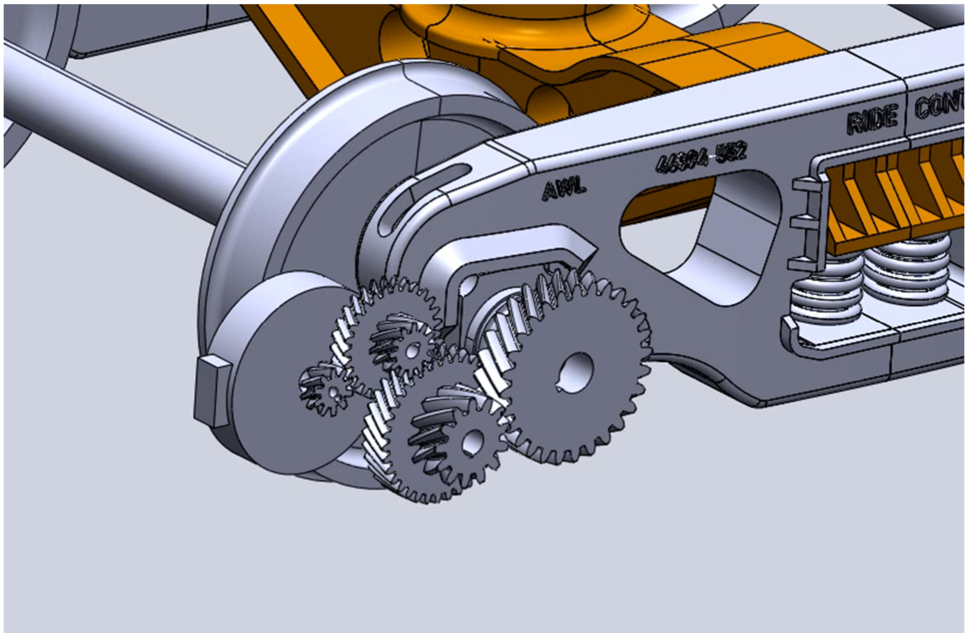

Figure 23: Gearset on Rail Model

The above image displays the gearset in a possible position on a generalized model of a rail car bogie, or truck assembly. Once a gearbox casting is developed and manufactured, the gears will lie in this approximate position on the physical unit. Intramotev will work to design the interfaces between the gearset and axles and motor to ensure the overall depth of the gear system will fit within the clearance restrictions of the AAR Plate Clearance guidelines.

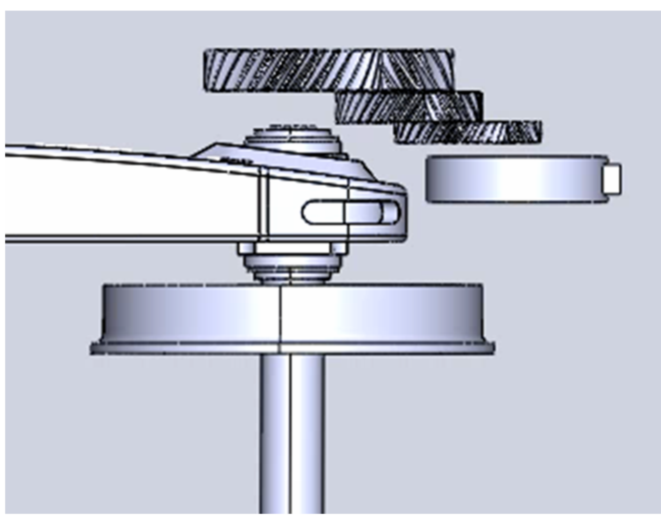

Figure 24: Overhead Mockup View

The above image represents the approximate positioning of the gearset and electric motor. These pieces will dictate the design of the interface plates between the different components.

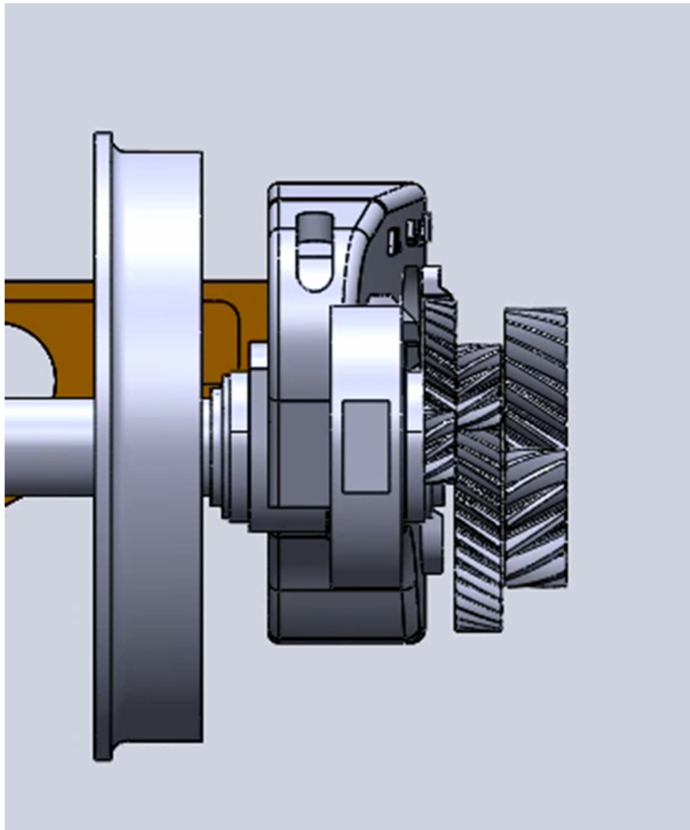

Figure 25: Right Hand Bogie View

9 DESIGN DOCUMENTATION

9.1 FINAL DRAWINGS AND DOCUMENTATION

9.1.1 Engineering Drawings

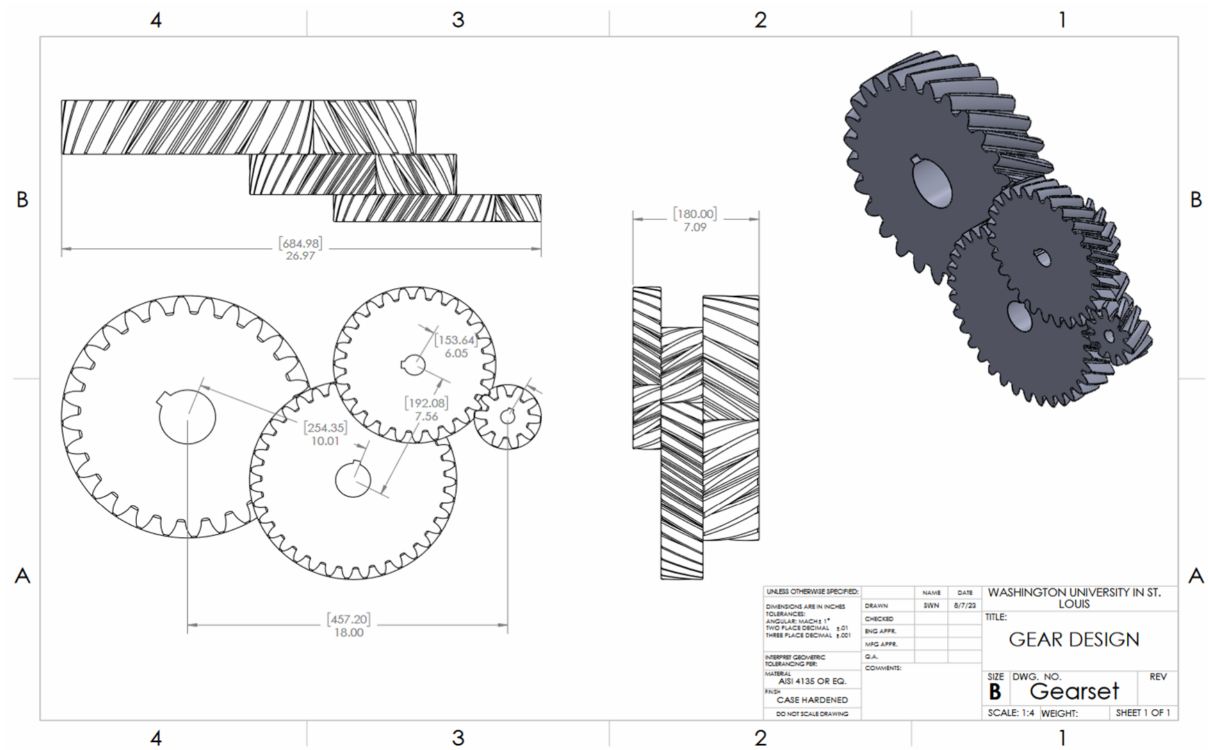

Figure 26: Gearset Assembly Drawing

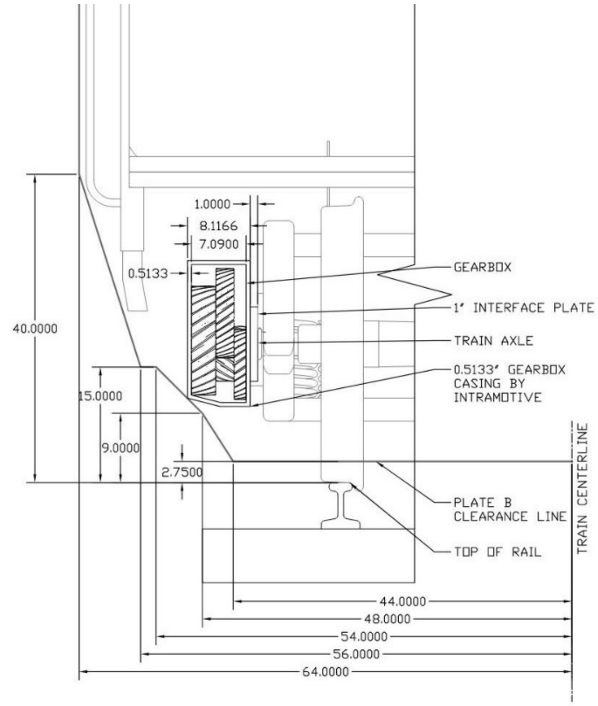

Figure 27: Gearset Elevation with Plate B Clearance

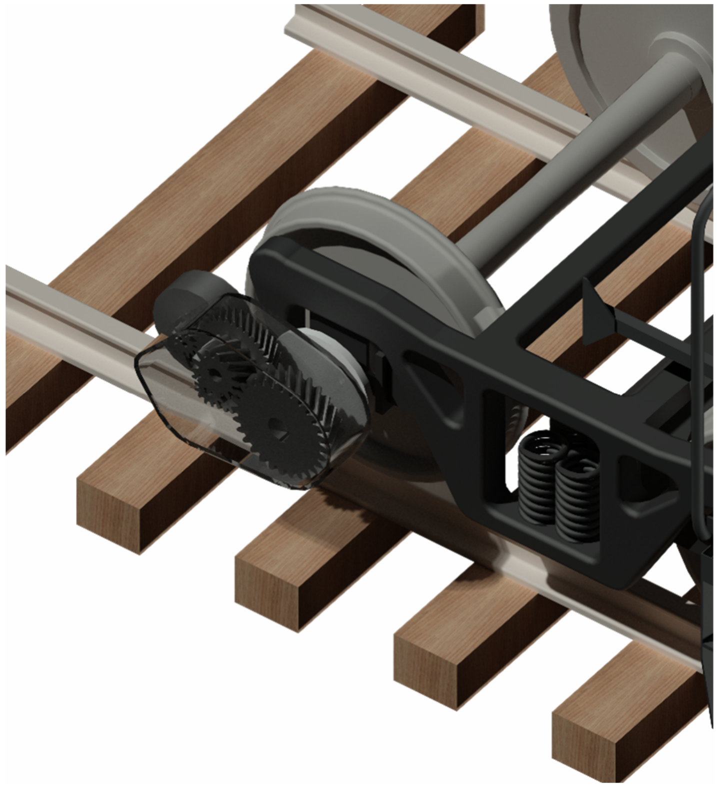

Figure 28: Gearset Assembly Drawing

See Appendix C for individual part engineering drawings.

9.1.2 Sourcing Instructions

Individual gears can be made by custom gear manufacturers across industry, such as KHK Gears or Arrow Gear. These manufacturers can build the gears as drawn by providing the material, pressure and helix angles, module, and number of teeth, along with the desired shaft axle dimensions. These gears can also be provided by custom CNC manufacturing companies such as Xometry, however these gears will be slightly less strong due to the differences in surface finish compared to proper hobbed gear profiles. A full custom CNC gearset from Xometry is approximately $10,000, though bespoke gear manufacturers would most likely be slightly cheaper due to the less specialized setup and knowledge required.

Axles can be produced by standard machine shops with access to lathes and mills. These dimensions need not be specialized save for the shaft interacting with the electric motor, which may need broaching due to the splined shaft profile.

The gear casing will most likely need to be custom CNC'ed out of aluminum from a machine shop until true casting dimensions can be developed for post development builds. The bearings for each axle can be sourced from standard bearing houses, or online retailers such as McMaster-Carr.

9.2 FINAL PRESENTATION

The below video link shows the final presentation of the gear design project team.

https://youtu.be/I4Vm2lMlepU

Figure 299: Presentation Video

10 TEARDOWN

The deliverables for this project were primarily 3D models; the sample scale prototype is a 3Dd printed representation made from PLA, a recyclable plastic. As such, this project involves no teardown save for recycling the printed gearset and base.

11 APPENDIX A - PARTS LIST

Table 7: CNC Gear Pricing

Part	Description	Cost
Gear 1	10 Tooth, 40mm Thick, Module 8 Gear	$ 833.00
Gear 2	27 Tooth, 40mm Thick, Module 8 Gear	$1,226.00
Gear 3	12 Tooth, 60mm Thick, Module 8 Gear	$1,010.00
Gear 4	35 Tooth, 60mm Thick, Module 8 Gear	$1,881.00
Gear 5	13 Tooth, 80mm Thick, Module 12 Gear	$1,591.00
Gear 6	28 Tooth, 80mm Thick, Module 12 Gear	$2,692.00

Note: This gear pricing is provided by the online CNC company Xometry. All gear pricing is with the gear configured as 4130 steel, case hardened post-treatment, and an overall surface finish of 63uin/ 1.6um Ra. These prices would most likely be cheaper if quoted from a bespoke gear manufacturer.

12 APPENDIX B - BILL OF MATERIALS

Table 8: 50% Scale 3D Print Pricing

Part	Description	Cost
Gear 1	10 Tooth, 40mm Thick, Module 8 Gear	$ 0.22
Gear 2	27 Tooth, 40mm Thick, Module 8 Gear	$ 1.21
Gear 3	12 Tooth, 60mm Thick, Module 8 Gear	$ 0.40
Gear 4	35 Tooth, 60mm Thick, Module 8 Gear	$ 2.72
Gear 5	13 Tooth, 80mm Thick, Module 12 Gear	$ 1.19
Gear 6	28 Tooth, 80mm Thick, Module 12 Gear	$ 4.84
Axles	Temporary Axles for Mockup	$ 0.99
Baseplate	Mounting Baseplate for Mockup	$ 3.85

Note: This pricing is based on filament pricing for standard PLA 3D printing filament. This model was scaled at 50% full size for fitment and time purposes, and the above pricing reflects that scaling.

13 APPENDIX C – COMPLETE LIST OF ENGINEERING DRAWINGS

3D files for the designed gears (STEP and Solidworks 2023 models), along with drawings and excel calculations, can be accessed at the link below.

https://www.dropbox.com/sh/b0w01sx83ipehav/AADaHCVp5kjZEMFEmrm_R14ba?dl=0

14 ANNOTATED BIBLIOGRAPHY

[1] Larson, Erik W., and Clifford F. Gray. "Chapter 7: Managing Risk." *Project Management: The Managerial Process*, McGraw-Hill, Boston, Mass. u.a, 2021.