Drivetrain Trade Study

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Abstract

The purpose of this trade study is to identify the optimal DC motor and wheel combination of the drivetrain, which will serve as the propulsion system of the Medical Express Delivery System (MEDS). The drivetrain is needed to drive the MEDS to the patients and back to the starting line in the shortest time possible. In addition, the study seeks to define how much of a propulsive force factor of safety the robot has if design changes are needed, the total weight of the drivetrain system, and the total cost. The result of this study is a data-driven recommendation to the team for the specific motor and wheel combination that will maximize the vehicle's performance and ensure mission success.

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1 Introduction

The primary goal of the Medical Express Delivery System (MEDS) is to autonomously navigate a course and deliver medication to a designated patient. The success of this mission is fundamentally dependent on the vehicle's ability to move quickly and reliably from its starting point to the delivery location. This movement is controlled entirely by the drivetrain subsystem, which is responsible for propelling the vehicle and is the subject of this study. The study seeks to answer the following question: "Which combination of DC motor and wheels will allow the MEDS vehicle to complete its 200 total foot delivery course in the shortest possible time while adhering to all performance, budget, and design constraints?"
The core performance metric for the MEDS vehicle is the time it takes to complete its 200-foot delivery route. The vehicle's speed, acceleration, and overall reliability are directly dictated by the selection of its drivetrain components. Therefore, a data-driven selection process is required to ensure the chosen components are optimized for the mission. While the basic configuration of a 17.5 lb, rear-wheel-drive vehicle is established and is seen in Figure 1, the specific drive motors and wheels have not yet been determined.

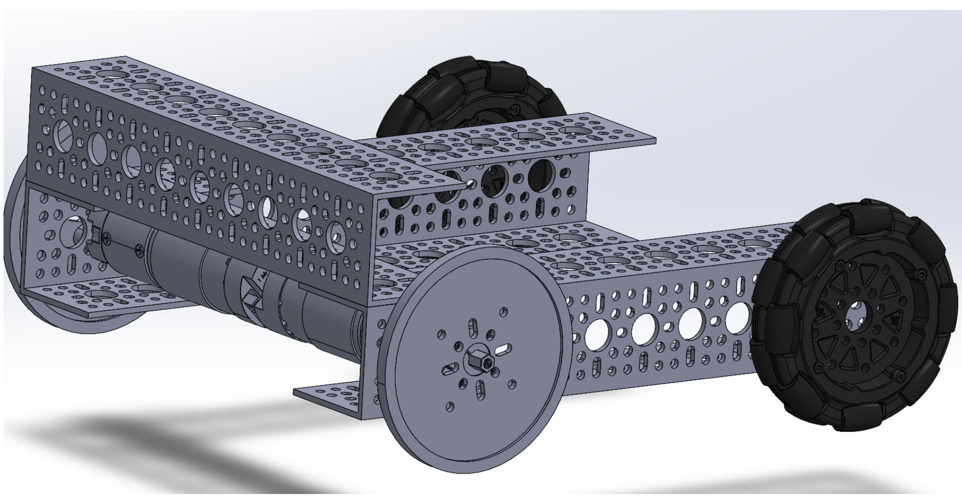

Figure 1: SolidWorks CAD model of the MEDS drivetrain, with example motors and wheels.

The optimal values for the DC motors and the wheels will be recommended to the team based on the results of this study. This report details the engineering analysis used to simulate the performance of various motor and wheel combinations to find the one that best balances speed, cost, weight, and safety factor. The design constants and variables are broken down further in the following section.

2 Engineering Analysis

To simplify the model and focus the scope of this study on the most important components, several aspects of the drivetrain design were set and held constant based on engineering specifications and team discussion. The vehicle is configured as a rear-wheel-drive system, where power is delivered only to the two rearmost wheels. This is a common and mechanically simple setup for this type of robotic platform. To ensure smooth and efficient turning, free-spinning omni wheels will be utilized for the front two wheels of the MEDS. Per a decision from the design lead, these front omni wheels will have the same diameter as the selected rear drive wheels to maintain a level chassis. The base weight of the vehicle, including the chassis, electronics, and all other non-drivetrain components, is held constant at 17.5 lbs. The final weight used in the dynamic calculations is this base weight plus the weight of the two selected motors and wheels. Finally, a coefficient of rolling resistance of 0.02 is assumed for the duration of the course. This value was chosen to represent the interaction between rubber wheels and the expected linoleum driving surface and is held constant for all simulations. By fixing these parameters, the analysis can isolate the performance effects directly attributable to the motor and wheel selections.

2.1 Design Variables

The variables of the drivetrain design that need further analysis to determine are the design variables. This study will make a recommendation as to which combination of these variables has the best result. The variables considered will be the specific 12-volt DC motor and driven wheels. The motor selection is limited by several key factors. Per design specification #33, the motors must be 12-volt DC motors. Furthermore, a constraint imposed by the Electronics Lead requires that the motor must have a built-in shaft encoder to record speed, direction, and position, and this encoder must have a minimum resolution of 360 pulses per rotation. A requirement from the design lead dictates that the front, free-spinning wheels will be standard omni-wheels while the rear, driven wheels will be standard wheels. While the types are fixed, their diameter, width, and material are varying, with the additional constraint that all four wheels must be of the same diameter. Finally, the physical integration of these components is governed by design specification #7. The vehicle's wheelbase must not exceed a 1ft by 1ft area. This specification also dictates that the combined length of the motors and the width of the wheels, when placed back-to-back, cannot be longer than 12 inches due to the motor and wheel layout configuration.

After reviewing commercially available options that meet these criteria, four motors and four wheels were selected for analysis. The key specifications for these components, such as performance metrics, physical dimensions, and cost, are summarized in the tables below. These are the inputs that will be iterated through in the engineering model.

Table 1: Motor Selections and Specifications

#	Motor Model	Free Speed (RPM)	Stall Torque (oz-in)	Weight (oz)	Encoder (PPR)	Price
1	YJ 5203 (13.7:1)	435	260	15.45	384.5	$54.99
2	YJ 5203 (19.2:1)	312	338	15.41	537.7	$54.99
3	HD Hex (40:1)	150	594.7	12.35	1120	$34.50
4	HD Hex (20:1)	300	297.4	12.35	560	$34.50

Table 2: Wheel Selections and Specifications

#	Wheel Model	Diameter (in)	Material	Width (in)	Weight (oz)	Price
1	3607 Disc Wheel	3.78	Rubber	0.24	1.31	$6.99/2
2	3607 Disc Wheel	2.83	Rubber	0.24	0.74	$4.99/2
3	3612 Rhino Wheel	3.78	Rubber	0.63	3.21	$7.99
4	Hogback Traction	3.78	Rubber/Plastic	0.94	2.89	$9.99

2.2 State Variables

The desired results of the design variables are the state variables. These variables will determine the best drivetrain design based on the measure of merit. The state variables are the Time to Traverse Course (70%), the Propulsive Force Factor of Safety (15%), the Total Weight of Components (10%), and the Total Cost (5%).

The Propulsive Force Factor of Safety must be at least 15 per the design lead. This means the drivetrain must be able to output a torque 15 times the required torque to nominally move the vehicle, which accounts for design changes, uneven driving surfaces, and other external impediments, while keeping the motor at the lower end of its torque vs speed curve. Additionally, the total Cost of the drivetrain components must be less than $226, a budget allocated by the team. The remaining state variables, Time to Traverse Course and Weight of Components, should be minimized to achieve the highest possible performance score.

2.3 Engineering Model

A MATLAB model was constructed to simulate the performance of 16 unique drivetrain combinations by iterating through four distinct motor and four distinct wheel options. The simulation calculates the key performance metrics required for the robot to traverse the specified 200-foot course. It is assumed in this model that the robot is powered by two drive motors, that the available driving force is limited by the lesser of motor output and wheel traction, and that the robot follows a trapezoidal velocity profile by accelerating to a maximum speed before cruising for the remaining distance. This model uses principles of static and rolling friction, torque-to-force conversion, Newton's Second Law, and kinematic

equations to relate the design variables (motor and wheel choice) to the state variables (course time, cost, weight, and propulsive force factor of safety).
This engineering model utilizes a key simplification for calculating vehicle performance. It assumes a constant acceleration based on the driving force derived from the motors' maximum stall torque. In reality, a DC motor's available torque decreases as its speed increases from zero. Since the same physical model is applied to all options, the resulting rankings remain valid for selecting the optimal design, as it serves as a baseline comparison between component pairings.

Drivetrain Performance Model Equations
The following sections detail the governing equations used to calculate the performance metrics for each motor and wheel combination. The primary outputs of this model are the Propulsive Force Factor of Safety, also reffered to as Factor of Safety Against Stalling and the total time required to travel the specified course distance. All kinematic and dynamic equations are derived from first principles as established in foundational engineering texts [1, 2].

Propulsive Force Factor of Safety
The propulsive Force Factor of Safety, FoS_{Stall}, is a crucial metric that quantifies the drivetrain's ability to overcome resistance. It is defined as the ratio of the available driving force to the resistive force from rolling friction. A value greater than 1.0 indicates the robot can move, and the magnitude of the value represents the leeway for adding additional mass before the system would fail to move. This is calculated according to Eq. 1.

$$FoS_{Stall} = \frac{F_{drive}}{F_{resistance}} \tag{1}$$

Where F_{drive} is the available driving force at the wheels and $F_{resistance}$ is the force of rolling resistance. These component forces are determined by the following equations.

The driving force, F_{drive}, is limited by either the motors' maximum propulsive force or the maximum traction the wheels can achieve before slipping. It is therefore the lesser of these two values, as shown in Eq. 2.

$$F_{drive} = \min(F_{propulsive}, F_{traction}) \tag{2}$$

The maximum propulsive force is a function of the combined stall torque of the two motors and the wheel radius, a direct application of the relationship between torque and force, given by Eq. 3 [1].

$$F_{propulsive} = \frac{2 \cdot \tau_{stall}}{r_{wheel}} \tag{3}$$

Where τ_{stall} is the stall torque of a single motor and r_{wheel} is the radius of the driven wheels. The maximum traction force is dependent on the coefficient of static friction, μ_s, and the normal force on the two drive wheels, N, as shown in the standard model for dry friction in Eq. 4 [2].

$$F_{traction} = \mu_s \cdot N \tag{4}$$

The normal force on the drive wheels is assumed to be half of the robot's total weight, W_{total}. The coefficients of static friction used in the model vary by wheel selection, as shown in Table 3.

Table 3: Estimated Coefficients of Static Friction (μ_s)

Wheel Model	**Selected μ_s Value**
96mm & 72mm Disc Wheels	0.7
96mm Rhino Wheel	0.8
96mm Hogback Traction Wheel	0.9

These tiered values reflect the principle that the coefficient of friction depends heavily on factors such as rubber composition and surface characteristics. This principle was affirmed by synthesizing research from several sources, including Hentschke & Plagge [5], Fukahori et al. [7], and Nishi [8] using Consensus AI, as detailed in Appendix C. The selected values are tiered based on the specific properties of each wheel. The narrow Disc Wheels are assigned a baseline value of 0.7. The Rhino Wheel's value is increased to 0.8 to account for its significantly wider contact patch, which provides more stable and consistent grip. The Hogback Traction Wheel is assigned the highest value of 0.9 as it is both wide and constructed from a softer 50A durometer rubber, a material explicitly designed to maximize surface conformity and frictional force.

Finally, the rolling resistance force is calculated as the product of the coefficient of rolling resistance, C_{rr}, and the total weight of the robot, W_{total}. A constant C_{rr} of 0.02, a typical value for a firm wheel on a smooth floor, was used for all combinations [1].

$$F_{resistance} = C_{rr} \cdot W_{total} \tag{5}$$

Time to Travel 80 Feet

The time to travel the 80 straightaway of the course is calculated assuming a trapezoidal velocity profile. This model consists of an initial phase of constant acceleration followed by a phase of constant maximum velocity, a standard approach for simplified drivetrain analysis.

First, the net force on the robot is determined by subtracting the rolling resistance from the available driving force, as shown in Eq. 6.

$$F_{net} = F_{drive} - F_{resistance} \tag{6}$$

Using Newton's Second Law of Motion [2], the constant acceleration of the robot, a, can be found.

$$a = \frac{F_{net}}{m_{total}} \tag{7}$$

Where m_{total} is the total mass of the robot. The robot's maximum theoretical velocity, v_{max}, is dictated by the motor's no-load free speed, ω_{free}, and the wheel radius, based on the fundamental no-slip condition for rolling motion [1].

$$v_{max} = \omega_{free} \cdot r_{wheel} \tag{8}$$

With the acceleration and maximum velocity known, the distance required to reach this velocity, d_{accel}, is found using the constant acceleration kinematic relationship in Eq. 9 [2].

$$d_{accel} = \frac{{v_{max}}^2}{2a} \tag{9}$$

If d_{accel} is greater than or equal to the course distance, d_{course}, the total time is calculated using Eq. 10.

$$t_{total} = \sqrt{\frac{2 \cdot d_{course}}{a}} \quad (\text{if } d_{accel} \geq d_{course}) \tag{10}$$

If d_{accel} is less than the course distance, the robot accelerates to v_{max} and then travels the remaining distance at a constant speed. The total time is the sum of the acceleration time and the cruise time, as shown in Eqs. 11 - 13.

$$t_{accel} = \frac{v_{max}}{a} \tag{11}$$

$$t_{cruise} = \frac{d_{course} - d_{accel}}{v_{max}} \tag{12}$$

$$t_{total} = t_{accel} + t_{cruise} \quad (\text{if } d_{accel} < d_{course}) \tag{13}$$

2.4 Model Validation

To validate the engineering model, its core physics calculations were tested against a textbook problem with a known solution. This problem, derived from foundational principles in Hibbler's *Engineering Mechanics: Dynamics* [1], was chosen because it cohesively tests the entire chain of calculations the model performs, from determining forces to predicting motion. The problem is shown below in Figure 2.

Textbook Validation Problem:
A 10 kg rover is being designed for a speed trial. It has two drive wheels, each with a diameter of 100 mm. The two drive motors can each produce a maximum stall torque of 2.5 N·m. The rover's electronics limit its maximum possible speed to 5.0 m/s. The coefficient of static friction (μ_s) between the wheels and the concrete floor is 0.8, and the coefficient of rolling resistance (C_{rr}) is 0.03.

Find:

1. The maximum initial acceleration of the rover.
2. The total time it will take for the rover to travel 25 meters from a standing start.

Figure 2: Problem used to verify the model's core physics calculations.

This problem closely resembles the objective of the main engineering model: to determine the performance of a wheeled robot based on its mechanical and electrical specifications. It effectively tests whether the model correctly translates motor torque into propulsive force, accurately identifies whether performance is limited by motor power or wheel traction, and correctly calculates net force by accounting for rolling resistance. Furthermore, it validates the kinematic calculations used to determine travel time for a system that first accelerates and then cruises at a maximum velocity. Once it was proven that the model could properly handle this sequence of calculations, the complete drivetrain simulation could be trusted. The hand calculations for this validation problem can be found in the Appendix.

All of this problem's values were entered into the model and the results compared to the expected solution. As Figure 3 below shows, the results and expected solution aligned, indicating that the model accurately simulates the drivetrain's dynamic performance.

```
--- Textbook Problem Validation Results ---
Limiting Driving Force (F_drive):   78.48 N
Net Force for Acceleration (F_net): 75.54 N

QUESTION 1: What is the maximum initial acceleration?
   - Manual Calculation:    7.55 m/s^2
   - MATLAB Script Result:  7.55 m/s^2

QUESTION 2: What is the time to travel 25 meters?
   - Manual Calculation:    5.33 s
   - MATLAB Script Result:  5.33 s
>>
```

Figure 3: Output of the model with validation inputs.

3 Results

To determine the best design, the 16 combinations of the two design variables were run though the model. The motors ranged from a free speed velocity of 435 to 150 RPM, with stall torques ranging from 260 to 594.7 oz·in. The wheel ranged in diameter from 2.83in to 3.78in, with widths ranging from 0.24in to 0.94in. All of these combinations met the state variable constraints outlined earlier. These design combinations then needed to be evaluated to determine which best met the engineering specifications and customer requirements. The results of the MATLAB simulation are seen in Figure 4 below.

Drivetrain Analysis Results (Final):

Motor	Wheel	Total_Weight_lbs	Total_Cost	Will_Move	FoS_Stall	FoS_Slip	Time_to_80ft_s
"YJ 13.7:1"	"96mm Disc"	19.59	116.97	"Yes"	17.5	0.4	11.49
"YJ 13.7:1"	"72mm Disc"	19.52	114.97	"Yes"	17.5	0.3	15.12
"YJ 13.7:1"	"96mm Rhino"	19.83	125.96	"Yes"	20	0.46	11.45
"YJ 13.7:1"	"96mm Hogback"	19.79	129.96	"Yes"	22.5	0.52	11.41
"YJ 19.2:1"	"96mm Disc"	19.59	116.97	"Yes"	17.5	0.31	15.79
"YJ 19.2:1"	"72mm Disc"	19.52	114.97	"Yes"	17.5	0.23	20.91
"YJ 19.2:1"	"96mm Rhino"	19.83	125.96	"Yes"	20	0.35	15.76
"YJ 19.2:1"	"96mm Hogback"	19.79	129.96	"Yes"	22.5	0.4	15.73
"HD Hex 40:1"	"96mm Disc"	19.21	75.99	"Yes"	17.5	0.17	32.46
"HD Hex 40:1"	"72mm Disc"	19.14	73.99	"Yes"	17.5	0.13	43.21
"HD Hex 40:1"	"96mm Rhino"	19.44	84.98	"Yes"	20	0.2	32.44
"HD Hex 40:1"	"96mm Hogback"	19.4	88.98	"Yes"	22.5	0.22	32.43
"HD Hex 20:1"	"96mm Disc"	19.21	75.99	"Yes"	17.5	0.34	16.4
"HD Hex 20:1"	"72mm Disc"	19.14	73.99	"Yes"	17.5	0.26	21.73
"HD Hex 20:1"	"96mm Rhino"	19.44	84.98	"Yes"	20	0.4	16.37
"HD Hex 20:1"	"96mm Hogback"	19.4	88.98	"Yes"	22.5	0.44	16.35

Figure 4: MATLAB Simulation Results

3.1 Measure of Merit

A decision matrix was used to measure the merit of each of the 16 design combinations. To objectively score each design, the results for each of the four state variables were normalized using the Standard Selection Decision Support Method [4]. This process maps each raw attribute value (a_{ij}) to a common, dimensionless scale from 0 to 1, where 1 represents the most desirable outcome and 0 represents the least desirable. This value was then multiplied by 10 for ease of readability. The ideal solution has the course completion time, total weight, and total cost minimized. For these attributes, which are to be minimized, the raw values were normalized using Equation 14:

$$r_{ij} = \frac{a_{i,max} - a_{ij}}{a_{i,max} - a_{i,min}} \tag{14}$$

Conversely, the propulsive force factor of safety is ideally maximized. For this attribute, the values were normalized using Equation 15, which assigns a higher score to a higher raw value:

$$r_{ij} = \frac{a_{ij} - a_{i,min}}{a_{i,max} - a_{i,min}} \tag{15}$$

Finally, these normalized scores (r_{ij}) for each attribute i were multiplied by their respective weights (l_i) as defined in the State Variables section. The weighted scores were then summed together to produce a final total merit score (M_j) for each design alternative j, as shown in Equation 16. The combination with the highest total merit score is considered the optimal design.

$$M_j = \sum_{i=1}^{n} l_i r_{ij} \tag{16}$$

The full decision matrix with weighted values can be seen below in Table 4.

Table 4: Decision Matrix

Determine the alternative that best meets the engineering specifications	State Variable Results (1-10 Scale)								
	Course Completion Time		Propulsive Force Factor of Safety		Weight of Components		Total Cost		Total
	0.7		0.15		0.1		0.05		1
Designs	**Absolute**	**Weighted**		**Weighted**	**Absolute**	**Weighted**	**Absolute**	**Weighted**	**Weighted**
Motor #1 with Wheel #1	9.98	6.98	0.00	0.00	3.48	0.35	2.32	0.12	7.45
Motor #1 with Wheel #2	8.83	6.18	0.00	0.00	4.49	0.45	2.68	0.13	6.77
Motor #1 with Wheel #3	9.99	6.99	5.00	0.75	0.00	0.00	0.72	0.04	7.78
Motor #1 with Wheel #4	10.00	7.00	10.00	1.50	0.58	0.06	0.00	0.00	8.56
Motor #2 with Wheel #1	8.62	6.04	0.00	0.00	3.48	0.35	2.32	0.12	6.50
Motor #2 with Wheel #2	7.01	4.91	0.00	0.00	4.49	0.45	2.68	0.13	5.49
Motor #2 with Wheel #3	8.63	6.04	5.00	0.75	0.00	0.00	0.72	0.04	6.83
Motor #2 with Wheel #4	8.64	6.05	10.00	1.50	0.58	0.06	0.00	0.00	7.61
Motor #3 with Wheel #1	3.38	2.37	0.00	0.00	8.99	0.90	9.64	0.48	3.75
Motor #3 with Wheel #2	0.00	0.00	0.00	0.00	10.00	1.00	10.00	0.50	1.50
Motor #3 with Wheel #3	3.39	2.37	5.00	0.75	5.65	0.57	8.04	0.40	4.09
Motor #3 with Wheel #4	3.39	2.37	10.00	1.50	6.23	0.62	7.32	0.37	4.86
Motor #4 with Wheel #1	8.43	5.90	0.00	0.00	8.99	0.90	9.64	0.48	7.28
Motor #4 with Wheel #2	6.75	4.73	0.00	0.00	10.00	1.00	10.00	0.50	6.23
Motor #4 with Wheel #3	8.44	5.91	5.00	0.75	5.65	0.57	8.04	0.40	7.63
Motor #4 with Wheel #4	8.45	5.92	10.00	1.50	6.23	0.62	7.32	0.37	8.40

3.2 Conclusion and Recommendation

Given the results of the Decision Matrix, this study recommends using Motor #1 and Wheel #4. These components correspond with the 5203 Series Yellow Jacket Planetary Gear Motor (13.7:1 Ratio) and the 96mm Hogback Traction Wheel. As shown in the matrix, this combination achieves the highest overall merit score of 8.56. Its performance is driven by its results in the two most heavily weighted categories, achieving a perfect 10/10 score for the Time to Traverse Course (70% weight) and a perfect 10/10 for the Propulsive Force Factor of Safety (15% weight). While this combination also received the lowest possible score for cost, its superior performance in the key metrics demonstrates that the trade-off is worthwhile for maximizing overall performance.

In the event that components from the primary recommendation are unavailable due to stock limitations or other constraints, this study proposes two alternative configurations. If the primary motor (Motor #1) is unavailable, the recommended alternative is the combination of Motor #4 and Wheel #4. This pairing represents the highest-scoring design that does not use Motor #1 and offers the benefits of a lower component cost and the maximum possible Factor of Safety, though at a penalty to speed. If, however, the primary wheel (Wheel #4) is unavailable, the study recommends pairing Motor #1 with Wheel #3. This combination achieved the third-highest merit score overall (7.78) and offers a comparable time-to-traverse performance while accepting a lower, yet still robust, Factor of Safety.

Finally, a notable trend is that the 72mm Disc Wheel (Wheel #2) consistently resulted in the lowest merit scores across all motor pairings. Its smaller diameter appears to negatively impact kinematic performance to a degree that its lower weight and cost cannot offset. Therefore, this study recommends the team avoid this wheel option, as it is outperformed by all other alternatives in this analysis.

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5 Appendix

Drivetrain Trade Study Proposal

The purpose of this trade study is to provide a recommendation to the team for the selection of the optimal combination of motors and wheels for the Medical Express Delivery System (MEDS) drivetrain. This decision is critical to ensuring the vehicle can complete its 200 ft delivery course in the fastest possible time, which is the team's primary metric for mission success.

Design Variables

- Wheels
- Motors

Constraints on Design Variables

- The motor must have a built-in optical shaft encoder to record the speed, direction, and angular position of the motor output. This constraint is imposed by the electronics lead.
- The motors must be a 12 volts DC motor, per the design specification #33.
- The wheelbase must not exceed a 1ft by 1ft area, as defined by design specification #7.
- The front freespinning wheels will be standard omni wheels while the rear driven wheels will be standard rubber wheels. This constraint is imposed by the design lead.

State Variables (in order of importance with weights in parentheses)

- Time required for a 25 lb vehicle to traverse the 200 ft course (55%)
- Cost (15%)
- Torque Factor of Safety (15%)
- Optical Shaft Encoder Resolution (15%)

Constraints on State Variables

- The vehicle must be able to reach a speed of 5mph. This originates from the design specification #23.
- The optical shaft encoder must have a minimum of 500 pulses per rotation. This constraint is imposed by the Electronics Lead. (https://www.usdigital.com/support/resources/reference/technical-docs/white-papers/resolution-accuracy-and-precision-of-encoders/)
- The drivetrain components must cost less than $226. This is a budget allocated to the drivetrain by the Team.
- The drivetrain must be able to output a torque 2 times the required torque to nominally move the vehicle to account for design changes, uneven driving surfaces, and other external impediments. This constraint is imposed by the Design Lead.

Engineering Model(s)

1

Figure 5: Drivetrain Trade Study Proposal, Page 1

A dynamic simulation will be developed in MATLAB to map the design variables (motor and wheel combinations) to the state variables (performance metrics). The simulation will be used to conduct the following analyses:

- The model will apply the laws of kinematics to predict the time required for the 25 lb vehicle to travel 200 ft and execute a 90-degree turn.
- The coefficient of static friction between the wheels and a linoleum surface will be included to model wheel slip during acceleration. The analysis will consider both a clean surface and a surface with dust buildup to simulate real-world conditions.
- The simulation will assess the drivetrain's ability to climb a 1-inch, 20-degree incline, modeling the floor-mounted electrical outlets on the course.
- The motor shafts will be analyzed to ensure they can sustain the required torque, including the 2.0 factor of safety.
- The specified pulses per rotation of the optical encoders will be evaluated to determine the theoretical precision of a 90-degree turn.

A SolidWorks motion analysis simulation will also be performed in order to provide a secondary analysis of drivetrain performance. This will be used to analyze the MEDS turning characteristics as well as its ability to climb a 1-inch, 20-degree incline.

Measure of Merit

A decision matrix will be created ranking and comparing the vehicle drivetrain against each of the state variables listed above. Within the decision matrix, the time required to complete the course and the cost of the components should be minimized while the factor of safety and optical shaft encoder resolution should be maximized. Each state variable score will be weighted according to their importance as decided by a team vote (see values above). The highest weighted score will determine the best overall set of state variables, and will determine the recommendation of components presented to the Team for the drivetrain.

Validation/Verification of Computer Simulation(s)

The dynamic simulation will be validated by applying the MATLAB program to multiple textbook examples with known and correct solutions from *Engineering Mechanics: Dynamics 9th Edition* by James L. Meriam and J.N. Bolton. A kinematic analysis will also be applied with a separate program to verify the results, taking the answers from the simulation and applying the laws of kinematics to ensure the results are generally possible. The MATLAB simulation will also be compared with a SolidWorks motion simulation to check that both simulations have similar results using two different simulation softwares.

2

Figure 6: Drivetrain Trade Study Proposal, Page 2

5.1 Design Specifications

REV B

Highlighted specifications indicate updates from Rev A

Design Specifications	
Team Name/Number: 09	**Date: 08/26/2025**

Customer Requirements

1. Completed final system in a timely manner.
2. Cost effective.
3. Made from durable materials.
4. Medication delivery system that comprises of three individual devices to deliver medications to the correct patients in hospitals.
5. Set anatomical dimensions for Patient A and B.
6. Delivery device must be able to travel from the pill dispensary location to the patient.
7. Biomechanical interaction with an upper extremity of Patient A to signal the delivery system.
8. Thermal interaction with Patient B to signal the delivery system at high body temperatures.
9. The system needs to be maneuverable and agile to navigate the course when delivering medication.
10. Medication delivery should move and deposit a set number of pills to the correct patient zone.
11. Efficient in terms of both time and distance traveled.
12. Visually appealing.
13. Easy for medical staff to handle and store.

Engineering Specifications

1. All systems must be fully functional by December 6th, 2025
2. Collective system must remain under a $1,000 budget
3. The collective system must contain 0 components made of wood
4. The collective system must use 0 adhesion materials (duct tape, glue, etc.)
5. Mechanical fasteners (screws, nuts, bolts, etc.) must be used to secure 100% of the components
6. The chassis frame must be able to support up to a 25 lb load
7. Delivery device must not exceed 1ft x 1ft base area
8. Wearable device must fit subject A's dimensions:
    a. Thumb circumference- 2.75 inches, pinky circumference- 1.8 inches, wrist circumference- 7 inches, length between top of thumb and wrist- 5 inches, length between top of pinky and thumb- 5.5 inches
    Measured the Patient's Dimensions- David Shunk
9. Wearable device must fit subject B's dimensions:

1

Figure 7: Design Specifications, Page 1

REV B

a. Thumb circumference- 2.25 inches, pinky circumference- 1.6 inches, wrist circumference- 6 inches, length between top of thumb and wrist- 4.5 inches, length between top of pinky and thumb- 5 inches
Measured the Patient's Dimensions- Leah Kern

10. Delivery device must be able to travel 40 feet in a linear path within a 5% margin of error (2 feet).
https://equine.ca.uky.edu/content/what-does-%E2%80%98statistically-significant%E2%80%99-actually-mean
11. Delivery device must be capable of moving to the left and right
12. Delivery device must be able to turn in response to a signal from the wearable device
13. Delivery device must be able to record the distance traveled while delivering medication using an odometer
14. Delivery devices must display the total distance traveled while delivering medication
15. Delivery devices must indicate which patient it is responding to via an LED that operates with 3.3 V and 16 mA
https://thepihut.com/blogs/raspberry-pi-tutorials/27968772-turning-on-an-led-with-your-raspberry-pis-gpio-pins
16. Wearable device must be capable of thermal measurements from 98 to over 102 degrees Fahrenheit in an appropriate/non-invasive way
https://www.mayoclinic.org/diseases-conditions/fever/in-depth/fever/art-2005099
17. Wearable device must be capable of thermal measurements with an accuracy of 1°F or more
https://www.dwyeromega.com/en-us/resources/thermistor#:~:text=Thermistors%20are%20highly%20accurate%20(ranging,not%20change%20significantly%20with%20age.
18. At 102 degrees Fahrenheit, the wearable device must be triggered to send a 5 GHz Wifi signal to the delivery robot
https://www.mayoclinic.org/diseases-conditions/fever/in-depth/fever/art-2005099
19. Wearable device must be capable of detecting a non-functional biomechanical movement of a patient's upper extremity that has 1 degree of freedom through sensors or buttons. A possible biomechanical movement would be touching the thumb to the pinky to complete a circuit and send out a signal.
20. Once biomechanical movement is detected, the wearable device must be capable of sending a 5 GHz Wifi signal to the delivery device
21. The signal between the delivery device and wearable devices should be able to span over 50ft
22. Delivery device must be able to travel a total of 200ft
23. The velocity of the delivery device should be under 5mph
https://www.sciencedirect.com/science/article/pii/S0921889010000680
24. The delivery device must be able to run for 10 minutes. (3 rounds of a 200ft course at an average of 3mph times a factor of safety of 1.5)

2

Figure 8: Design Specifications, Page 2

Developing a mobile robot for transport applications in the hospital domain - ScienceDirect

25. Delivery device must successfully engage with the docking system 95% of the trials
26. The docking station must interface with a solo cup of the following dimensions 100% of the time
    a. The cup has a height of 3", outer diameter of 3.5" at the opening, and inner diameter 2.25" at the base
27. Delivery device must individually dispense 2 correct pills into the proper patient's cup
28. Delivery device must have the ability to hold at minimum 20 "pills" of size ⅝ inches in length and ⅜ inches in diameter https://candylandstore.com/shop/jewel-jelly-belly-beans/
    a. In terms of volume, the delivery device must be able to hold $4.9677\ in^3$ volume for the "pills"
        i. $20\,JB\ *\ \frac{1\ gal}{930\ JB} * \frac{128\ ounces}{1\ gal} * \frac{1.805\ in^3}{1\ ounce} = 4.9677\ in^3$ https://www.vcalc.com/wiki/candies-in-container-calculator
29. The pill chamber within the delivery device must be able to support 22.6 g which amounts to 20 jelly beans
    a. $1.13\ g/JB\ *\ 20\ JB\ =\ 22.6\ g$ https://www.jellybelly.com/general-facts
30. The height of the delivery device must not exceed 29", so that it can fit under a hospital bed https://www.sondercare.com/learn/hospital-beds/what-is-ideal-height-for-home-hospital-bed/#:~:text=The%20most%20common%20height%20range,%2Dinches%20to%2029%2Dinches.
31. The weight of the delivery device must less than 50 lbs https://www.bls.gov/ors/factsheet/strength.htm#:~:text=However%2C%20if%20they%20delivered%20slightly,weighing%20less%20than%20one%20pound.
32. The weight of the wearable device must less than 5.1 lbs https://hf.tc.faa.gov/publications/2005-human-factors-guidance-for-the-use-of-handheld/full_text.pdf
33. The battery in the delivery device should be able to provide 12V at 10 amps and 5V at 3 amps
34. The battery in the wearable device should have a maximum voltage of 5V https://oxeltech.de/design-guide-for-battery-safety-in-wearable-electronics/
35. The battery in the wearable device should be able to provide 5V at 3 amps
36. The full system should include 3 microcontrollers, one for the delivery device and one for each wearable device.
37. The battery in the delivery device should be able to be recharged with a charging time of 1 hour

3

Figure 9: Design Specifications, Page 3

https://fpvfc.org/beginners-guide-to-lipo-batteries#:~:text=The%20safest%20way%20to%20charge,discharged%20battery%20around%203.2v%20).

38. The microcontrollers must be capable of sending signals via wifi.
39. The microcontrollers must be capable of being powered by a 5V battery supply
40. The full system should be able to complete 9 out of 10 consecutive trials successfully
41. Entire system must be considered aesthetically appealing at a ranking of 3 or higher on the Likert Scale by 3-5 unaffiliated people
42. The wearable device should not cause skin irritation or be uncomfortable via rating 2 or less on a Likert scale of 1-5 by 3-5 unaffiliated people
43. The full system should complete the course in under 3 minutes

Figure 10: Design Specifications, Page 4

5.2 Measure of Merit Equations Class Notes

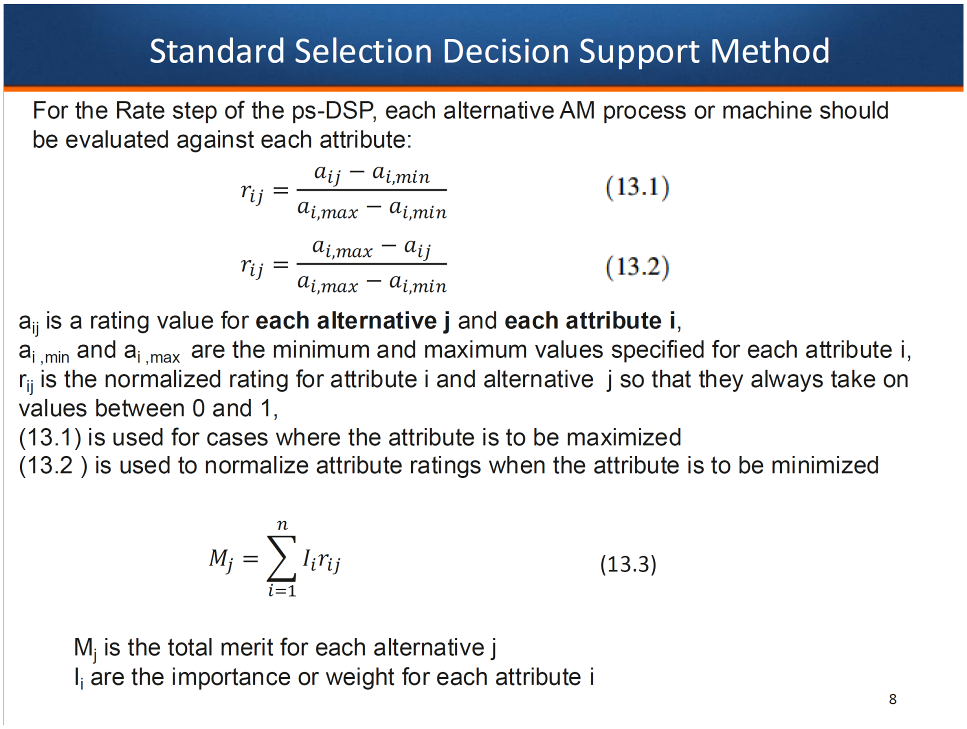

Figure 11: Measure of Merit Equations Class Notes from AME40643 - Additive Manufacturing, taught by Prof. Yanliang Zhang. Equations from Additive Manufacturing Technologies, Third Edition.[4]

5.3 Handwritten Calculations

David Shuk — Textbook Validation

Textbook: Young, H. D., & Freedman, R. A. (2020), University Physics with Modern Physics (15th ed.).

Textbook Problem:

Mass = 10 kg

Wheel Diameter = 0.1 m

Stall Torque (τ) = 2.5 N·m per motor

Motors = 2

V_{max} = 5 m/sec

Static Friction Coefficient : 0.8

Rolling Resistance Coefficient : 0.03

Total Distance = 25 m

Gravity = 9.81 m/sec^2

Calculations:

Weight = $(m)(g) = (10\,kg)(9.81\,m/sec^2) = \boxed{98.1\,N}$

$r = D/2 = 0.05\,m$ radius

Total Torque = (2 motors)(2.5 N/m) = 5 Nm

Propulsive Force = $\dfrac{\text{Total Torque}}{r} = \dfrac{5.0\,N\cdot m}{0.05\,m} = \boxed{100\,N}$

$F_{Traction} = (\mu_s)(N) = (0.8)(98.1\,N) = \boxed{78.48\,N}$

$F_{Drive} \Rightarrow 100\,N > 78.48\,N \Rightarrow \boxed{F_{Drive} = 78.48\,N}$

$F_{Resistance}$ = (Rolling Resistance)(N) $= (0.03)(98.1\,N) = \boxed{2.94\,N}$

$F_{net} = F_{Drive} - F_{Resistance} = 78.48\,N - 2.94\,N = 75.54\,N$

$a = F_{net}/m = 75.54/10\,kg = \boxed{7.55\,m/sec^2}$

$t_{accel} = V_{max}/a = 5/7.55 = 0.662\,sec$

$d_{accel} = \frac{1}{2} a t^2 = (0.5)(7.55)(0.662)^2 = 1.66\,m$

$d_{cruise} = d_{tot} - d_{accel} = 25\,m - 1.66\,m = 23.34\,m$

$t_{cruise} = d_{cruise}/V_{max} = 23.34/5 = 4.67\,sec$

$t_{Total} = t_{accel} + t_{cruise} = 0.662 + 4.67 = \boxed{5.33\,sec}$

Figure 12: Textbook Validation Problem Manual Solution

5.4 Model - MATLAB Code

```
% Drivetrain Performance Calculator (Final Version)
clc;
clear;
close all;

g = 9.81; % Acceleration due to gravity (m/s^2)
W_base_lbs = 17.5; % Base robot weight (lbs)
dist_ft = 80; % Course distance (ft)
C_rr = 0.02; % Assumed coefficient of rolling resistance for rubber on
linoleum
dist_m = dist_ft * 0.3048; % Course distance in meters

% Motor Data (Properties: Name, Free Speed (RPM), Stall Torque (N.m), Mass
(kg), Cost ($))
motors(1) = struct('Name', "YJ 13.7:1", 'RPM', 435, 'StallTorque', 1.836,
'Mass', 0.438, 'Cost', 54.99);
motors(2) = struct('Name', "YJ 19.2:1", 'RPM', 312, 'StallTorque', 2.386,
'Mass', 0.437, 'Cost', 54.99);
motors(3) = struct('Name', "HD Hex 40:1", 'RPM', 150, 'StallTorque', 4.2,
'Mass', 0.350, 'Cost', 34.50);
motors(4) = struct('Name', "HD Hex 20:1", 'RPM', 300, 'StallTorque', 2.1,
'Mass', 0.350, 'Cost', 34.50);

% Wheel Data (Properties: Name, Diameter (m), Mass (kg), Cost ($), Coeff. of
Static Friction)
wheels(1) = struct('Name', "96mm Disc", 'Diameter', 0.096, 'Mass', 0.037,
'Cost', 6.99/2, 'mu_s', 0.7);
wheels(2) = struct('Name', "72mm Disc", 'Diameter', 0.072, 'Mass', 0.021,
'Cost', 4.99/2, 'mu_s', 0.7);
wheels(3) = struct('Name', "96mm Rhino", 'Diameter', 0.096, 'Mass', 0.091,
'Cost', 7.99, 'mu_s', 0.8);
wheels(4) = struct('Name', "96mm Hogback", 'Diameter', 0.096, 'Mass', 0.082,
'Cost', 9.99, 'mu_s', 0.9);

% --- Results Table Initialization ---
num_combos = length(motors) * length(wheels);
result_table = table('Size',[num_combos 8], ...
    'VariableTypes', {'string', 'string', 'double', 'double', 'string',
'double', 'double', 'double'}, ...
    'VariableNames', {'Motor', 'Wheel', 'Total_Weight_lbs', 'Total_Cost', ...
                      'Will_Move', 'FoS_Stall', 'FoS_Slip',
'Time_to_80ft_s'});

idx = 1;
for m = 1:length(motors)
    for w = 1:length(wheels)
        % Get current motor and wheel
        current_motor = motors(m);
        current_wheel = wheels(w);

        % Weight and Mass
        W_total_lbs = W_base_lbs + 2*current_motor.Mass*2.20462 +
```

1

Figure 13: MATLAB code used to implement the trade study model (Page 1)

```
2*current_wheel.Mass*2.20462;
        W_total_N = W_total_lbs * 4.44822;
        m_total_kg = W_total_N / g;

        % Cost
        C_total = 2 * current_motor.Cost + 2 * current_wheel.Cost;

        % Forces and Factors of Safety
        r_wheel_m = current_wheel.Diameter / 2;
        F_propulsive = (2 * current_motor.StallTorque) / r_wheel_m; % Max
force from motors
        F_traction = current_wheel.mu_s * (W_total_N / 2); % Max force from
friction/grip
        F_drive = min(F_propulsive, F_traction); % Actual available driving
force (limited by slip)
        F_resistance = C_rr * W_total_N; % Rolling resistance force to
overcome
        FoS_Stall = F_drive / F_resistance; % Leeway for adding weight
        FoS_Slip = F_traction / F_propulsive; % Tendency for wheels to slip

        if F_drive > F_resistance
            Will_Move = "Yes";
            F_net = F_drive - F_resistance; % Net force causing acceleration

            % Time to Travel Calculation using trapezoidal velocity profile
            a_mps2 = F_net / m_total_kg;
            omega_free_rad_s = current_motor.RPM * (2*pi/60);
            v_max_mps = omega_free_rad_s * r_wheel_m;
            t_accel = v_max_mps / a_mps2;
            d_accel_m = 0.5 * a_mps2 * t_accel^2;

            if d_accel_m >= dist_m
                t_total_s = sqrt(2 * dist_m / a_mps2);
            else
                t_cruise_s = (dist_m - d_accel_m) / v_max_mps;
                t_total_s = t_accel + t_cruise_s;
            end
        else
            Will_Move = "No";
            t_total_s = Inf; % Cannot move, time is infinite
        end

        result_table.Motor(idx) = current_motor.Name;
        result_table.Wheel(idx) = current_wheel.Name;
        result_table.Total_Weight_lbs(idx) = round(W_total_lbs, 2);
        result_table.Total_Cost(idx) = round(C_total, 2);
        result_table.Will_Move(idx) = Will_Move;
        result_table.FoS_Stall(idx) = round(FoS_Stall, 1);
        result_table.FoS_Slip(idx) = round(FoS_Slip, 2);
        result_table.Time_to_80ft_s(idx) = round(t_total_s, 2);

        idx = idx + 1;
    end
end
```

2

Figure 14: MATLAB code used to implement the trade study model (Page 2)

```
disp('Drivetrain Analysis Results (Final):');
disp(result_table);
```

```
Drivetrain Analysis Results (Final):
       Motor            Wheel          Total_Weight_lbs    Total_Cost
Will_Move     FoS_Stall     FoS_Slip     Time_to_80ft_s
    _____________    ______________    ________________    __________
_________    _________    ________    ______________

    "YJ 13.7:1"      "96mm Disc"           19.59            116.97
"Yes"        17.5          0.4         11.49
    "YJ 13.7:1"      "72mm Disc"           19.52            114.97
"Yes"        17.5          0.3         15.12
    "YJ 13.7:1"      "96mm Rhino"          19.83            125.96
"Yes"          20         0.46         11.45
    "YJ 13.7:1"      "96mm Hogback"        19.79            129.96
"Yes"        22.5         0.52         11.41
    "YJ 19.2:1"      "96mm Disc"           19.59            116.97
"Yes"        17.5         0.31         15.79
    "YJ 19.2:1"      "72mm Disc"           19.52            114.97
"Yes"        17.5         0.23         20.91
    "YJ 19.2:1"      "96mm Rhino"          19.83            125.96
"Yes"          20         0.35         15.76
    "YJ 19.2:1"      "96mm Hogback"        19.79            129.96
"Yes"        22.5          0.4         15.73
    "HD Hex 40:1"    "96mm Disc"           19.21             75.99
"Yes"        17.5         0.17         32.46
    "HD Hex 40:1"    "72mm Disc"           19.14             73.99
"Yes"        17.5         0.13         43.21
    "HD Hex 40:1"    "96mm Rhino"          19.44             84.98
"Yes"          20          0.2         32.44
    "HD Hex 40:1"    "96mm Hogback"         19.4             88.98
"Yes"        22.5         0.22         32.43
    "HD Hex 20:1"    "96mm Disc"           19.21             75.99
"Yes"        17.5         0.34          16.4
    "HD Hex 20:1"    "72mm Disc"           19.14             73.99
"Yes"        17.5         0.26         21.73
    "HD Hex 20:1"    "96mm Rhino"          19.44             84.98
"Yes"          20          0.4         16.37
    "HD Hex 20:1"    "96mm Hogback"         19.4             88.98
"Yes"        22.5         0.44         16.35
```

Published with MATLAB® R2025a

Figure 15: MATLAB code used to implement the trade study model (Page 3)

5.5 Model - MATLAB Validation Code

```
% Drivetrain Model Validation Script
% Textbook Problem Source: Principles from "University Physics with Modern
% Physics" by Young & Freedman, 15th ed.

clc;
clear;
close all;

% --- Constants from Textbook Problem ---
g = 9.81; % Acceleration due to gravity (m/s^2)
m_total_kg = 10; % Mass of the rover (kg)
dist_m = 25; % Course distance (m)
C_rr = 0.03; % Coefficient of rolling resistance
mu_s = 0.8; % Coefficient of static friction

% --- Drivetrain Parameters from Textbook Problem ---
motor_stall_torque_Nm = 2.5; % Stall torque per motor (N.m)
num_motors = 2; % Number of drive motors
wheel_diameter_m = 0.10; % Wheel diameter (m)
v_max_mps = 5.0; % Electronically limited maximum velocity (m/s)

% Weight
W_total_N = m_total_kg * g;

% Forces
r_wheel_m = wheel_diameter_m / 2;
F_propulsive = (num_motors * motor_stall_torque_Nm) / r_wheel_m; % Max force
from motors
F_traction = mu_s * W_total_N; % Max force from friction/grip for the entire
robot
F_drive = min(F_propulsive, F_traction); % Actual available driving force
F_resistance = C_rr * W_total_N; % Rolling resistance force to overcome

% Check if the rover can move
if F_drive > F_resistance
    Will_Move = "Yes";
    F_net = F_drive - F_resistance; % Net force causing acceleration

    % Initial Acceleration Calculation
    a_mps2 = F_net / m_total_kg;

    % Time to Travel Calculation using trapezoidal velocity profile
    t_accel = v_max_mps / a_mps2;
    d_accel_m = 0.5 * a_mps2 * t_accel^2;

    if d_accel_m >= dist_m
        % Rover accelerates for the entire duration
        t_total_s = sqrt(2 * dist_m / a_mps2);
    else
        % Rover accelerates then cruises at v_max
        t_cruise_s = (dist_m - d_accel_m) / v_max_mps;
        t_total_s = t_accel + t_cruise_s;
```

1

Figure 16: Trade Study Code Modified for Validation (Page 1)

```
    end
else
    Will_Move = "No";
    a_mps2 = 0;
    t_total_s = Inf;
end

% --- Display Final Results ---
disp('--- Textbook Problem Validation Results ---');
fprintf('Limiting Driving Force (F_drive):   %.2f N\n', F_drive);
fprintf('Net Force for Acceleration (F_net): %.2f N\n\n', F_net);

fprintf('QUESTION 1: What is the maximum initial acceleration?\n');
fprintf('   - Manual Calculation:    7.55 m/s^2\n');
fprintf('   - MATLAB Script Result:  %.2f m/s^2\n\n', a_mps2);

fprintf('QUESTION 2: What is the time to travel 25 meters?\n');
fprintf('   - Manual Calculation:    5.33 s\n');
fprintf('   - MATLAB Script Result:  %.2f s\n', t_total_s);
```

```
--- Textbook Problem Validation Results ---
Limiting Driving Force (F_drive):   78.48 N
Net Force for Acceleration (F_net): 75.54 N

QUESTION 1: What is the maximum initial acceleration?
   - Manual Calculation:    7.55 m/s^2
   - MATLAB Script Result:  7.55 m/s^2

QUESTION 2: What is the time to travel 25 meters?
   - Manual Calculation:    5.33 s
   - MATLAB Script Result:  5.33 s
```

Published with MATLAB® R2025a

2

Figure 17: Trade Study Code Modified for Validation (Page 2)

Appendix C: GenAI

5.6 Consensus Coefficient of Friction Estimation

Consensus CONSENSUS.APP

What is the coefficient of friction between rubber and Linoleum?

The coefficient of friction between rubber and linoleum is typically high, but varies with conditions such as speed, load, and rubber composition.

Typical Values and Influencing Factors

The coefficient of friction (COF) between rubber and hard surfaces like linoleum is generally high, often ranging from **0.7 to 1.2 under dry conditions**, but this value can fluctuate significantly depending on several factors:

- **Surface Roughness:** The microtexture of linoleum and the rubber's own surface can alter the COF. Smoother surfaces may reduce friction, while rougher surfaces increase it (Hentschke & Plagge, 2021; Nishi, 2023).
- **Sliding Speed and Temperature:** The COF for rubber is not constant; it changes with sliding speed and temperature. At low speeds and moderate temperatures, adhesion dominates, leading to higher friction. At higher speeds, viscoelastic effects become more significant (Hentschke & Plagge, 2021; Plagge & Hentschke, 2022; Nishi, 2023).
- **Rubber Composition:** The presence of fillers, the type of rubber, and its viscoelastic properties all impact the COF. Highly filled or softer rubbers tend to have higher friction (Hentschke & Plagge, 2021; Plagge & Hentschke, 2022; Fukahori et al., 2020; Nishi, 2023).
- **Adhesion and Deformation:** Adhesion at the interface and the deformation of rubber due to surface asperities both contribute to the overall friction, with adhesion often accounting for 70–80% of the total COF (Hentschke & Plagge, 2021; Fukahori et al., 2020).

Table: Factors Affecting Rubber-Linoleum Friction

Factor	Effect on COF	Citations
Surface roughness	Higher roughness increases COF	(Hentschke & Plagge, 2021; Nishi, 2023)
Sliding speed	COF varies; often peaks at intermediate speeds	(Hentschke & Plagge, 2021; Plagge & Hentschke, 2022)
Temperature	COF decreases at higher temperatures	(Hentschke & Plagge, 2021; Plagge & Hentschke, 2022; Tiwari et al., 2018)
Rubber composition	Softer/more filled rubber increases COF	(Hentschke & Plagge, 2021; Fukahori et al., 2020; Nishi, 2023)
Adhesion	Major contributor to high COF	(Hentschke & Plagge, 2021; Fukahori et al., 2020)

FIGURE 1 Key factors influencing rubber-linoleum friction coefficient

?

Figure 18: Consensus Conversation Determining the Coefficient of Friction (Page 1)

Conclusion

The coefficient of friction between rubber and linoleum is high and context-dependent, typically ranging from 0.7 to 1.2 under dry conditions. It is strongly influenced by surface roughness, sliding speed, temperature, and the specific rubber formulation. For precise applications, direct measurement under relevant conditions is recommended.

These papers were sourced and synthesized using Consensus, an AI-powered search engine for research. Try it at https://consensus.app

References

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Fukahori, Y., Gabriel, P., Liang, H., & Busfield, J. (2020). A new generalized philosophy and theory for rubber friction and wear. *Wear*, 203166. https://doi.org/10.1016/j.wear.2019.203166

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Figure 19: Consensus Conversation Determining the Coefficient of Friction (Page 2)