Foldable, Dual-Mode Wheelchair Design for Improved Boarding/Deboarding on Airline Flights

by

Chair Force One

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First Quarter Progress Report for

ME 170A Mechanical Engineering Design

Integrating Context with Engineering

Fall Quarter, 2025

December 8, 2025

Project Objective

Design, manufacture, and test a wheelchair that allows manual wheelchair users to board and exit an aircraft with increased independence and seat themselves on standard aircraft seating.

Outcome of Concept Approval Review: **Approved**

On December 2, 2025, we presented a design concept for a manual wheelchair with linear actuators at its rear to enable its conversion to an aisle wheelchair that can be stored in a cabin overhead bin. The decision board, composed of Jeff Wood, Stephen Horne, and Cameron Haynesworth, **approved the concept** and plan to proceed to development to ME170B.

Project Summary

1. Users

Our primary users are manual wheelchair passengers` with full upper body capability that weigh under 300 lbs. Our secondary users are airline and airport staff, along with any companions the primary user may be traveling with (e.g. relatives).

2. User Requirements (URs) and Engineering Requirements (ERs)

We developed the following high priority User Requirements and Engineering Requirements that we will satisfy in ME170B. The in-depth rationale for each high priority requirement can be found in Appendix C. The full list of URs and ERs we developed can be found in Appendix H.

Table 1: High Priority User and Engineering Requirements

User Requirements		**Engineering Requirements**	
UR-1-1	All essential wheelchair actions can be completed independently by the end-user.	ER-1-1a	Propelling from a stationary position must be possible with both of the primary user's hands with no more than 12 lbf of force per hand on a level, smooth surface [1].
		ER-1-1b	Push/pull to lock and braking actions must be able to be completed with one or two of the wheelchair user's hands with no more than 12 lbf of force per hand on a level surface [1].
UR-1-2	The solution must be narrow enough to fit in the aisle on a Boeing 737 airplane in economy seating.	ER-1-2	The wheelchair's outermost width while in the aisle must be less than 18 inches [2][3].
UR-1-5	The solution can be stowed by a single user in the overhead bin in the main cabin of a Boeing 737.	ER-1-5	The wheelchair and all components in its stowed configuration must fit into a volume that is 54 x 22 x 14 inches in dimension [4][5].

UR-3-1	All physical components of the solution must be capable of withstanding all expected static loading conditions in all phases of the user's experience.	ER-3-1a	All physical components of the solution must support a 300 lb weight limit without yield when the product is used to transport the end-user [6].
		ER-3-1b	The wheelchair's backrest must be able to withstand 105 lbf of horizontal aft force applied at the top of the backrest without any yielding or failure in the wheelchair [7].
		ER-3-1c	The wheelchair must be able to tilt 15° forward, backward, and left/right without tip-over with 170 lb weight applied on the seat when wheel brakes are applied [8][9].
UR-4-2	Any onboard power systems of the wheelchair must be compliant with battery safety limits on airlines.	ER-4-2	Lithium-Ion batteries that are a part of the solution must have an energy capacity under 300 Wh (watt-hours) [10].

3. Design Concepts

3.1 Overview of Concepts

In order to address how to get a wheelchair user from the jet bridge to their aircraft seat, and back, three concepts were developed and investigated: an electric AirChair, a manual wheelchair with solo struts and a manual wheelchair with telescoping struts.

3.1.1 The Electric AirChair

The Electric AirChair concept was inspired by the American University of Sharjah UAE AirChair. The wheelchair can pass through the aisle and slot over aircraft seats using spherical wheels and C-shaped design [11]. This allows the primary user to remain in the same wheelchair for the duration of the flight. The original concept has spherical wheels for this lateral motion, but our prototype used mecanum wheels. Mecanum wheels have rollers that allow a device to translate forward, backward, side-to-side, and allow rotation in place.

Figure 1: The American University of Sharjah UAE AirChair (left) and the prototype version with mecanum wheels (right) [11].

3.1.2 The Manual Wheelchair with Solo Struts

This concept is a standard, rigid manual wheelchair with a seat width under 18 inches (ER-1-2) that converts to an aisle chair through the removal of the main rear wheels and the attachment of solo struts on an axle bar, as shown in Figure 2. The solo struts are detachable and have smaller, rigid wheels that prevent tipping backward. A majority of rigid wheelchairs have axle bars, and so this design leans toward a universal attachment. Secondary users can assist the primary user by attaching the solo struts to the axle bar before removing the large wheels right before entering the aircraft aisle.

Figure 2: Conversion from a manual, rigid wheelchair to an aisle wheelchair using connecting solo struts (Red) that attach to the wheelchair's axle bar (Blue).

3.1.3 The Manual Wheelchair with Telescoping Struts

This concept follows the same aisle chair conversion process as the wheelchair with solo struts (see Figure 3). Two rear struts are attached to the bottom of the wheelchair on the axle bar. Attached to each of these is a telescoping strut with its other end connected to the wheelchair frame. When not in use, the telescoping strut remains in the retracted position using a quick release pin that is manually removed. To convert to an aisle wheelchair, the quick release pin is removed, the telescoping strut is extended, and the pin is re-inserted to fit the struts in position. When the telescoping struts have been extended, the rear main wheels can be removed.

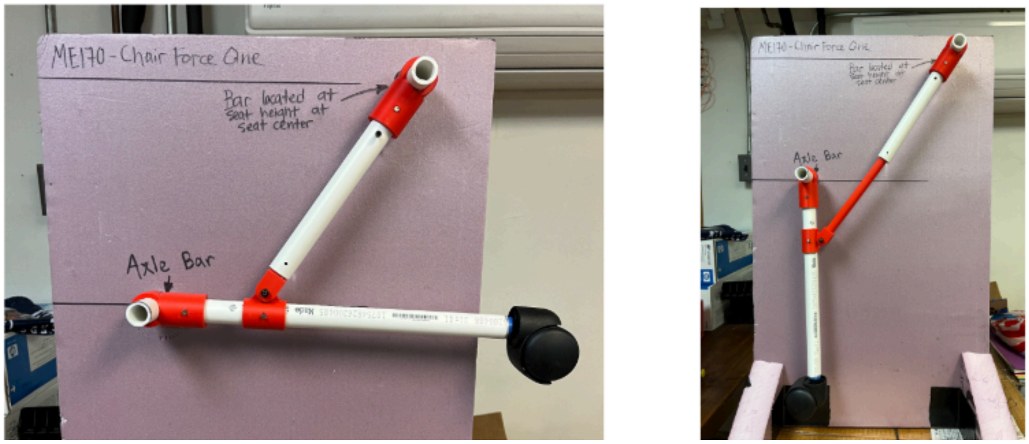


Figure 3: Telescoping struts in the horizontal, flushed position (left) and then the fully extended vertical strut.

3.2 Evaluation of Concepts

The three concepts were evaluated for feasibility against specific ERs. For further calculations and analysis, see Appendix M.

3.2.1 The Electric AirChair

There are two potential methods for using the Electric AirChair during the boarding process: backing down the aisle and then moving laterally onto the seat, or moving forward down the aisle, performing a 180° turn, and then shifting laterally. A basic angle tolerance analysis of the mecanum wheels was conducted to determine if the first option is feasible for our end-user to do independently; a maximum of ~5° tolerance is allowed from the aisle's centerline to avoid collision with the aisle seats (see Figure 4). It is unlikely our end-user would be able to achieve this in current Boeing 737 interiors. This method likely requires an automatic, feedback control system, adding complexity, cost and weight through the addition of a battery, motors and sensors. The second boarding method also proved infeasible as a 180° rotation in place with the mecanum wheels requires a seat width and depth of 12.5 inches due to ER-1-2 (see Figure 5). Standard, adult wheelchairs are more than 14 inches in width to avoid compromising on end-user comfort; 12.5 inches is not practical for a human occupant.

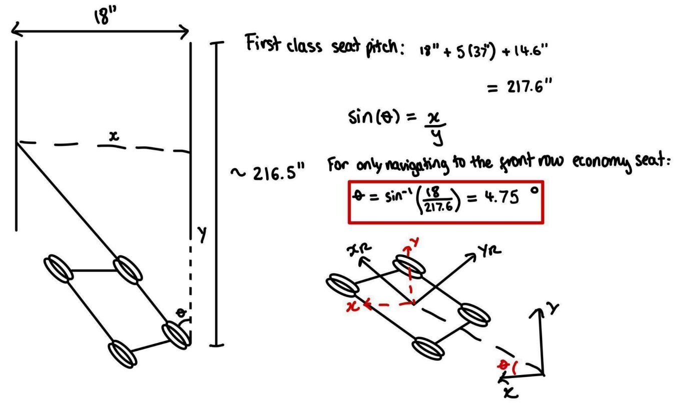


Figure 4: Analysis showing that the wheelchair must stay within <5° of the aisle centerline to back down the economy aisle without hitting seats.

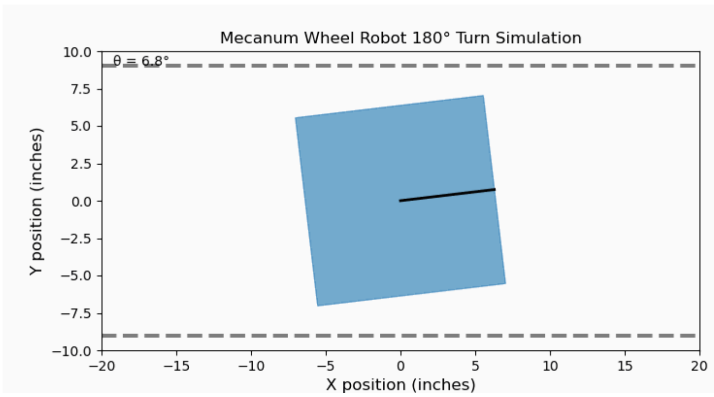


Figure 5: Simulation showing the Electric AirChair executing a 180° aisle turn without hitting seats. Demonstrating the maximum wheelchair size that can safely rotate (12.5 inch width, 12.5 inch depth).

3.2.2 The Manual Wheelchair with Solo Struts

We identified the attachment method of the struts to the axle bar to be a major risk. An initial analysis, shown on the left side of Figure 6, considers the moment produced if the 300 lb weight limit is applied (ER-3-1a) and distributed evenly between the two attachment points, neglecting the contribution of the front wheel. If friction alone were relied upon to resist rotations, the required frictional force would be extremely high, making this approach impractical. To address this, an interlocking component is introduced to prevent strut rotation, illustrated in blue in Figure 6. The required thickness of the part to resist bending stress is ~0.54 inches, which is feasible.

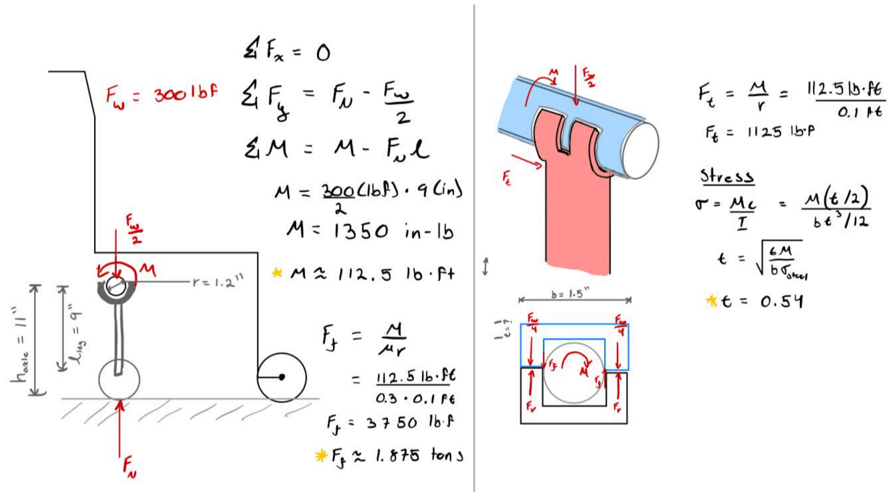


Figure 6: Free-body diagram of a single solo strut under the worst-case loading. Assumes the full design load is carried by the struts and front-wheel support is neglected. The resulting axle moment, required friction force, and bending stress are used to evaluate the interaction forces at the axle interface.

3.2.3 The Manual Wheelchair with Telescoping Struts

This concept was evaluated using ER-3-1a to determine required tube diameters to avoid yielding of the struts. As shown in Figure 7, the rear struts experience a combined normal force of 200 lbs, leading to 100 lbs compression on each strut. Euler buckling and compressive stress equations, along with a safety factor of 1.5 and 6061-Al material, resulted in an outer diameter of 0.685in and inner diameter 0.682in for the rear struts, which is feasible.

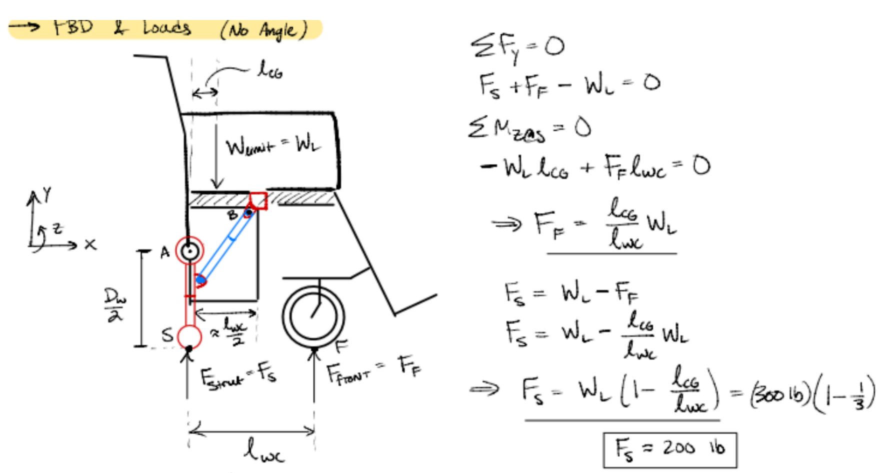


Figure 7: Rear (red) and telescoping (blue) struts under a wheelchair. Static equilibrium analysis with no rear strut wheel trail, assuming a 300 lb user, 6061-aluminum tubing, pin joints, 18 inch seat depth, and a safety factor of 1.5.struts.

3.3 Assessment of Concepts vs ERs

We developed a decision matrix to select a concept, as shown in Table 2. Each applicable ER was assigned a weight based on its priority in our full requirements sheet (Low = 1, Medium = 2, High = 3). Each concept was given scores based on how well they satisfied each ER (1 = poorly, 3 = excellent). The Electric AirChair scored highest for ER-1-1a because it is motorized, reducing force needed by the end-user to propel; manual wheelchair designs require physical pushing of the main large wheels. All concepts scored the same for ER-1-2 because they can all fit in an aisle. The solo strut concept was highest for ER-1-5 because it requires the least number of additional components, improving stowability. The AirChair scored highest for ER-1-6 because there are no actions that require deploying; the other two concepts require physical adjustments to the wheelchair. The telescoping struts scored highest in ER-3-1a, because it doesn't have as many failure modes as the AirChair or the solo struts. Both the solo strut and the telescoping strut scored high for ER-3-1c because the small required width for an manually-operated AirChair increases risk of tipping. Telescoping struts scored lowest for ER-4-1d because the telescoping mechanism introduces more parts and weight. The AirChair scored lowest for ER 4-2a because it would require a battery and charging considerations in comparison to the other concepts that would have very negligible energy demands (see Appendix M for more detail on energy consumption calculation).

Table 2: Decision Matrix Used to Evaluate Concepts Against ERs

Engineering Requirement	Weight	Electric AirChair	Solo Struts	Telescoping Struts
ER-1-1a: Propelling takes no more than 12 lbf per hand	3	3	2	2
ER-1-2: Wheelchair width in aisle < 18 inches	3	3	3	3
ER-1-5: Stowed wheelchair fits in 54x22x14 inch volume	3	1	3	2
ER-1-6: All actuations take < 15 seconds to deploy	1	3	2	2
ER-3-1a: Wheelchair must support 300 lb weight w/o yield	3	1	2	3
ER-3-1c: Tilt 15° without tip-over with 170 lb weight in seat	3	2	3	3
ER-4-1d: Wheelchair weighs < 50 lbs	2	2	2	1
ER-4-2a: Battery must be < 300 Wh capacity	3	2	3	3
	Total	45	54	52

The manual wheelchair with a solo-strut system emerged as our strongest concept. However, we received feedback in Design Review 7 about potentially integrating linear actuators to extend the struts, enabling the primary user to deploy them without assistance from secondary users. In addition, standard-sized rigid wheelchairs are unlikely to satisfy ER-1-5; to satisfy this, we opted to design a foldable wheelchair that can collapse down to the required volume. Incorporating these enhancements, we selected our final concept: a **foldable, dual-mode, manual wheelchair that converts into an aisle chair.**

In the refined concept, the struts are no longer external components that clip onto an existing chair. Instead, they extend directly from the wheelchair's frame using linear actuators. This allows the primary user to wheel themselves onto the plane, extend the struts until the rear wheels lift slightly off the ground, remove the larger wheels, and then navigate down the aisle to their seat.

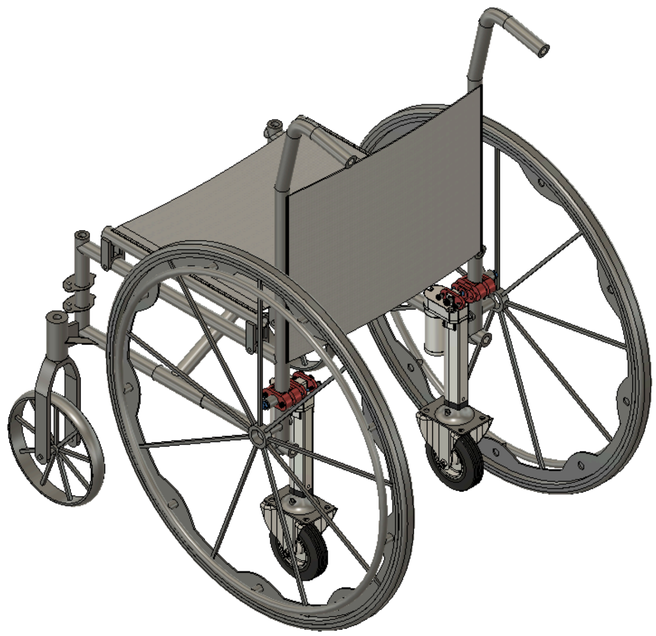


Figure 8: Foldable wheelchair with integrated linear actuators

4. Ethics

Of the three ASME Code of Ethics canons discussed in ME170A, our project was greatly influenced by the following two:

1) *Engineers shall* ***hold paramount the safety, health, and welfare of the public*** *in the performance of their professional duties.*

   Our wheelchair design should not injure our primary and secondary users during use and handling. To ensure our design's robustness, we are designing the wheelchair's structures to withstand 150% of limit loads in static loading conditions, ensuring the safety of our primary users (Medium Priority, ER-3-3). As for secondary users, our wheelchair's maximum weight is set to 50 lbs to reduce risk of physical strain due to handling/lifting the device (ER-4-1d).

2) *Engineers shall* ***act in professional matters for each employer or client as faithful agents*** *or trustees and shall avoid conflicts of interest or the appearance of conflicts of interest.*

   This project is in collaboration with Boeing; however, we must balance our client's needs with the needs of wheelchair users and airlines. To do so, we conducted multiple user interviews to inform our design and user requirements; for instance, we included UR-1-7 to increase our primary user's independence, leading to a design with linear actuators In addition, we are designing the wheelchair to be stowable in the aircraft cabin with the expectation that boarding/deboarding times could decrease for both airlines and our primary user (ER-1-5).

5. Plan Going Forward

Our team has identified six critical milestones for ME170B and the associated action items. For the chronological schedule, refer to Appendix E.

1) Design review (Week 11)
    a) Review Fall quarter design and identify wheelchair design risks.
    b) Develop test procedures for each subsystem to test to ERs.
2) Update Subsystems (Weeks 11-13)
    a) Linear Actuators: Select appropriate linear actuators based on the chosen wheel configuration, ensuring sufficient extension length to allow the user to remove the main wheels safely and comfortably.
    b) Battery: Estimate the total energy required for the linear actuators to deploy and retract a minimum of two full cycles (boarding and deboarding). Based on this analysis, purchase an appropriate battery, motor controller, and any associated wiring.
    c) Linear Actuator to Frame Attachment: Redesign the attachment mechanism between the linear actuators and the wheelchair frame to prevent rotational motion. Perform a structural and mechanical analysis of this interface to verify stability and load capacity.
    d) Linear Actuator to Wheel Attachment: Identify and purchase rigid wheels with brakes. Redesign the actuator-to-wheel mounting component for new wheels. Finalize the attaching design and select an appropriate material based on engineering analysis/simulation.
3) Build a Functional Prototype (Weeks 13-15)
    a) Integrate all subsystems into a modified wheelchair frame. This includes fabricating components through 3D printing and machining, as well as assembling the linear actuator circuits with the controller and associated wiring.
4) Test Functional Prototype (Weeks 15-17)
    a) Evaluate the functional prototype against our ERs through testing, including static and dynamic load testing, repeated deployment and retraction actuator cycles for

durability, and verification of system functionality under expected operating conditions.

5) Assemble and Test the Final Prototype (Weeks 17-18)
    a) Assemble and integrate all mechanical and electrical subsystems on the wheelchair, including final frame modifications, linear actuator and wheel installation, and mounting of the battery, controller, and wiring.
    b) Evaluate the Final Prototype across all ERs, like the Functional Prototype.
    c) Manufacture an additional wheelchair using the same processes as the Final Prototype for the final showcase.
6) Create a final report and presentation (Weeks 18-20)
    a) Document the engineering aspects and prepare a final report and presentation that showcases all the key and critical components of the project.

6. Budget

In Q1, we spent $390 on prototyping materials. In Q2, **we expect total project spend to reach $2455, with $545 remaining.** The primary expenditures include:

- Four electric linear actuators with hall effect sensors ($723)
- One hall effect controller for actuator synchronization ($185)
- Two foldable wheelchairs to create a test platform to test for all ERs and the final ME170B product ($369)
- Aluminum stock/tubing for small components we will machine in the PRL (wheel attachments to linear actuators, backrest tube connectors) ($151)
- One pair of scissor lock brakes to replace the stock brakes to satisfy ER-1-2 ($129)
- Test fixture materials (wood, nails, etc.) for an overhead bin box and an inclined ramp for tipping tests ($164)

7. Appendices

Appendix A –Team Members, Roles and Responsibilities

- Victoria Porto: Systems Engineer, electrical system design and concept analysis
- Rodolfo Morelos: Project Manager, CAD modeling and structural design
- Haley Taylor: Liaison Interface & Document Focal Point, structural design/analysis and CAD modeling
- Brad Yac-Diaz: Finance & Materials Manager, structural design/analysis and prototype manufacturing/testing

Appendix B – Introduction

In the United States, 12.2% of adults have a mobility impairment that limits their ability to walk [12]. Because the current air-travel infrastructure often fails to accommodate these mobility needs, many users perceive flying as difficult or unsafe. Consequently, 70% of surveyed participants said they chose not to travel by air due to accessibility concerns [13]. These statistics highlight a major gap in modern air travel: the lack of inclusive design for passengers with mobility challenges. For many individuals who use wheelchairs, flying often involves multiple uncomfortable and undignified transfers, from their personal wheelchair to an airport-provided chair, then to an aisle chair, and finally to the aircraft seat. This process not only increases the risk of injury and stress but also removes independence and dignity from the passenger experience. Current accessibility solutions on airplanes are limited.

As air travel continues to expand globally, ensuring equitable access for all passengers is imperative. The goal of this project is to design a cabin layout specific solution that allows passengers to board and exit an aircraft, move through its cabin, and secure themselves in standard aircraft seating. This solution aims to eliminate the need for in-plane transfers while maintaining the safety, comfort, and amenities of standard seating. By creating a product that integrates seamlessly with existing aircraft infrastructure and complies with FAA safety regulations, this project seeks to enhance the overall travel experience for passengers with disabilities, promoting independence, dignity, and inclusivity in air travel. Ultimately, this advancement aims to improve the air travel experience to such an extent that passengers with disabilities feel empowered and inspired to travel more freely—ensuring that everyone has the opportunity to explore the world and share in the experiences of an increasingly global society.

Appendix C – Background

C.1 Problem Background

For many wheelchair users, traveling by airplane is an uncomfortable and often stressful experience due to the complex and time-consuming boarding procedures required at most airports. Passengers must typically check in their personal wheelchair and transfer into an airport-provided wheelchair prior to passing through security or at the jet bridge. Once boarding begins, they're the first set of passengers to board and at the jet bridge they make another wheelchair transfer, this time into a narrow aisle wheelchair designed specifically for the aircraft cabin.

These transfers are facilitated by airport staff, who are frequently undertrained in proper handling and safety procedures of wheelchair users. During deplaning, wheelchair users must wait until all other passengers exit, making them the last to leave the aircraft. This process not only extends their overall travel time but can also feel disempowering and degrading.

Compounding this issue, personal wheelchairs are routinely damaged during handling by airports and airlines, creating significant mobility challenges at the destination. As a result, many wheelchair users choose to avoid air travel altogether. In a recent survey asking, "Thinking back to 2019, 2021, and 2022, estimate the number of times per year you chose not to travel by airplane based on accessibility," nearly seventy percent of respondents reported opting out of air travel due to accessibility barriers [13]. This highlights a critical flaw in air travel's ability to provide all passengers with a dignified travel experience and reinforces the importance of developing a solution to this issue.

C.2 User Research and Requirements

Our primary users are traveling wheelchair users that have full use of their upper torso and may not have lower body functionality. Due to issues described in Section C.1, many of our primary users are hesitant to fly on airliners; this stance on air travel has been corroborated by the three user interviews we conducted with wheelchair users [14][15][16]. The interviewed users indicated that there is a lack of independence in the current boarding process, that it can be quite difficult to receive high-quality assistance from airport staff due to variances in their training depending on the airport, and that parting with their wheelchairs can be anxiety-inducing [15][16]. For our users, a wheelchair is an extension of their physical body, and so any solution that can ensure comfort in their personal wheelchairs is the most favorable [14]. During interviews with wheelchair users, multiple users mentioned that they feel very unsafe in the current airport aisle chair and that they would prefer to stay in their own chair and avoid multiple wheelchair transfers. Noting these issues and desires from our user research, we determined five high priority user requirements that drove our concept selection. The full table of user requirements is in Appendix H, and the numbering used here is reflective of the table's.

Our first high priority requirement is **UR-1-1**, which states that all essential actions (e.g. propelling, braking/parking, etc.) to operate the wheelchair can be completed solely by the wheelchair user. A main value of this project is to increase our end-user's independence with the device, so aiming for the main functions to be operable all by the end-user works toward this. This value is a priority for our end-users as well based on our user interviews. **UR-1-2** requires that the wheelchair must be able to fit in the aisle of a Boeing 737 aircraft in economy seating. A

Boeing 737 is representative of the aircrafts used in US domestic flights, which fits with our intended end-user. The current solution for boarding and deboarding involves a separate aisle chair that fits in a cabin's aisle; in order for our wheelchair solution to be an improvement upon existing devices, it must be able to operate in the same condition as a regular aisle chair in a narrow aisle. **UR-1-5** requires that the wheelchair must be stowable in standard storage spaces in the cabin of a Boeing 737. A major pain point shared by our end-users in user interviews was the risk of damage to their personal wheelchairs when they were checked with other checked luggage [16]. The risk of damage to their personal wheelchair is likely to reduce if the device can remain in their possession when boarding. **UR-3-1** stipulates that the wheelchair must be able to withstand various static loading conditions. Based on user interviews, the robustness and materials of a wheelchair are important considerations when purchasing one [15]. In addition, wheelchairs on the market are rated to certain weight limits and other loading conditions, which our design should be comparable to. Lastly, **UR-4-2** specifies that all device power systems need to conform to regulations for safety. In order for our device to be allowed in the cabin, these regulations must be followed.

C.2.1 Engineering Requirements

To fulfill our user requirements, we developed engineering requirements for our design. This section only discusses high priority requirements; the full table of URs and ERs is available in Appendix H.

UR-1-1 specifies that all essential wheelchair actions can be performed independently by our end-user. From this, three engineering requirements (ER) were formed:

ER-1-1a: Propelling by the wheelchair user from a stationary position must be feasible with no more than 12 lbf per hand on a level, smooth surface. A wheelchair user has a finite amount of strength to move their wheelchair, especially without strain. 12 lbf was identified to be sufficient upon consulting the available force a 5th percentile US woman can apply in the forward direction while seated, as shown in Figure C.1, meaning 95% of the US population can propel the wheelchair [1].

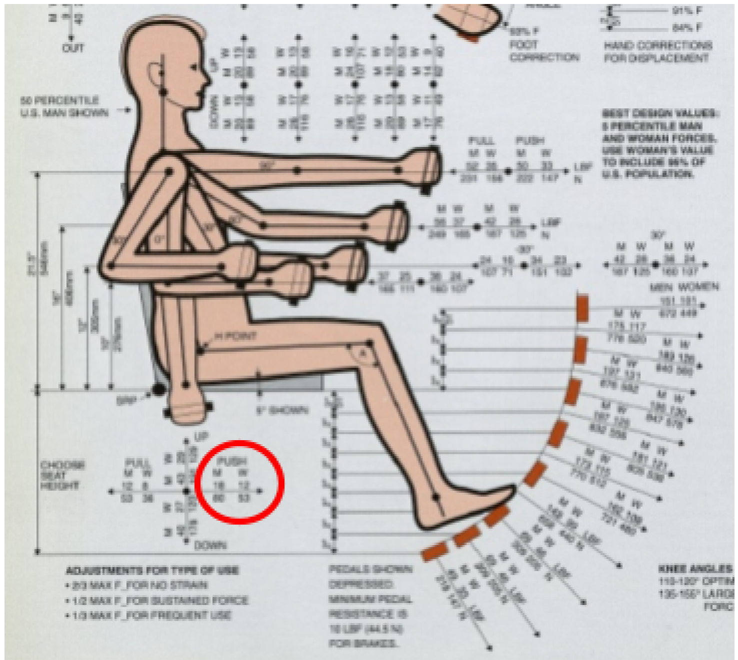


Figure C.1: Diagram of a seated individual, and the available force US men and women can apply from different arm positions. The propelling action requires an individual to have their arm perpendicular to the ground using a forward force to push a wheelchair's main wheels, which is a maximum of 12 lbf for a 5th percentile US woman [1].

ER-1-1b: Push/pull to lock and braking actions must be completable with one or two of the wheelchair user's hands with no more than 12 lbf of force per hand on a level surface. This ER follows directly from ER-1-1a, except it is for the use of the brakes on a wheelchair as braking is an essential part of wheelchair use, especially when transferring out of a wheelchair [17].

UR-1-2 requires that our wheelchair must be narrow enough to fit in the aisle of a Boeing 737 in economy seating. This translates directly to **ER-1-2** that specifies that the wheelchair in the aisle cannot have a width greater than 18 inches. If our wheelchair cannot fit within the aisle width during boarding, it will not be possible for our end-user to board or deboard using the device. From meetings with our Boeing liaison, it is common for cabin interiors to vary from airline to airline; as a baseline, and following available Boeing 737 cross section diagrams (Figure C.2), 18 inches is the aisle width we are designing for [2][3].

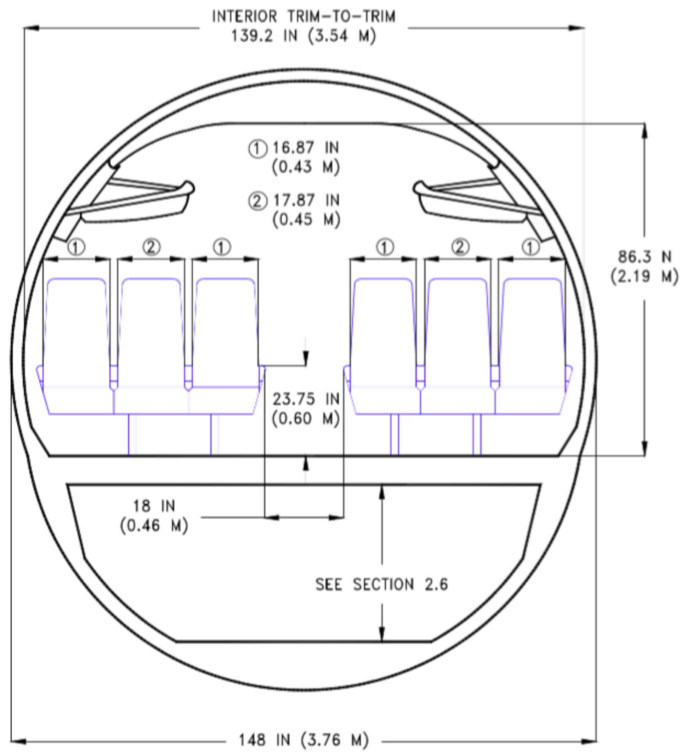


Figure C.2: Cross section of a Boeing 737 cabin [3]. The aisle is 18 inches from armrest to armrest, which is reflected in ER-1-2.

UR-1-5 stipulates that the wheelchair must be able to be stored in standard storage spaces in the main aircraft cabin. Modern Boeing 737s used by airlines typically have more than 100 seats [18]. In the Code of Federal Regulations, 14 CFR §382.67 requires that airline carriers must have a wheelchair space that is at least 42 x 36 x 13 inches to store a folding, collapsible, or break-down manual wheelchair [19]. Limiting our primary user to flying on Boeing 737s, this translates to two viable locations to stow a wheelchair: this required mobility aid space onboard, or in an overhead bin. Newer models of Boeing 737s have overhead bins called "Space Bins" that can stow 6 carry-on bags sized to 22 x 14 x 9 inches, leading to a total usable bin volume of 54 x 22 x 14inches [4][5]. These dimensions feed into **ER-1-5** that requires the wheelchair and its components to be stowable in a 54 x 22 x14 inch volume when not in use. This ER allows for the wheelchair to remain as close as possible to the wheelchair user, reducing the risk of damage and potentially reducing boarding/deboarding times as the user has direct access from the use of the overhead compartment. There is also flexibility with this set of dimensions to fit the wheelchair in the mandatory wheelchair space should the major length be less than 42 inches, which we have found to be feasible from our first full-scale prototype.

UR-3-1 mandates that all components of the wheelchair must be capable of withstanding all expected static loading conditions. This translates to the following three ERs:

ER-3-1a: All physical components of the solution must support a 300 lb weight limit without yield when the product is used to transport the end-user. The weight of an individual sitting on the wheelchair seat is an expected static loading condition on the wheelchair. Many standard wheelchairs are rated for a weight limit of 250 to 300 lbs, so designing the wheelchair to withstand a similar weight limit ensures that the product has a similar degree of safety relative to other wheelchairs on the market [6].

ER-3-1b: The wheelchair's backrest must be able to withstand 105 lbf of horizontal aft force applied to the top of the backrest without yield or failure in the wheelchair. In order to satisfy ER-1-5, we saw a need for the backrest of our first wheelchair prototype to be detachable to reduce the size of the wheelchair structure; this introduces a design risk in the wheelchair backrest structure that must be mitigated. Regular chair backrests can expect to endure a maximum of 34.7% of a person's body weight when an individual sits down roughly [7]. Using the maximum weight limit of ER-3-1a, this translates to approximately 105 lbf.

ER-3-1c: The wheelchair must be able to tilt 15° forward, backward, and left/right without tip-over with 170 lb in weight applied on the seat when wheel brakes are applied. It is common for 15° ramps to be encountered by wheelchair users, and so tipping should not occur for the safety of the user [8][9]. By ensuring this, the wheelchair is better suited to steeper inclines a wheelchair user may experience.

UR-4-2: Requires that any onboard power systems of the wheelchair must be compliant with battery safety limits on airlines. This translates to **ER-4-2a** where lithium-ion batteries that are a part of the solution must have an energy capacity of less than or equal to 300 Wh, and **ER-4-2b** where any batteries that are used in the wheelchair must be rechargeable. These ERs come directly from the FAA regulations on wheelchairs and mobility devices with lithium-ion batteries that can be removed and are not adequately protected in the device [10].

The high priority user and engineering requirements for this project are shown in Table C.1.

Table C.1: High Priority User and Engineering Requirements

User Requirements		**Engineering Requirements**	
UR-1-1	All essential wheelchair actions can be completed independently by the end-user.	ER-1-1a	Propelling from a stationary position must be possible with both of the primary user's hands with no more than 12 lbf of force per hand on a level, smooth surface [1].
		ER-1-1b	Push/pull to lock and braking actions must be able to be completed with one or two of the wheelchair user's hands with no more than 12 lbf of force per hand on a level surface [1].

UR-1-2	The solution must be narrow enough to fit in the aisle on a Boeing 737 airplane in economy seating.	ER-1-2	The wheelchair's outermost width while in the aisle must be less than 18 inches [2][3].
UR-1-5	The solution can be stowed by a single user in the overhead bin in the main cabin of a Boeing 737.	ER-1-5	The wheelchair and all components in its stowed configuration must fit into a volume that is 54 x 22 x 14 inches in dimension [4][5].
UR-3-1	All physical components of the solution must be capable of withstanding all expected static loading conditions in all phases of the user's experience.	ER-3-1a	All physical components of the solution must support a 300 lb weight limit without yield when the product is used to transport the end-user [6].
		ER-3-1b	The wheelchair's backrest must be able to withstand 105 lbf of horizontal aft force applied at the top of the backrest without any yielding or failure in the wheelchair [7].
		ER-3-1c	The wheelchair must be able to tilt 15° forward, backward, and left/right without tip-over with 170 lb weight applied on the seat when wheel brakes are applied [8][9].
UR-4-2	Any onboard power systems of the wheelchair must be compliant with battery safety limits on airlines.	ER-4-2	Lithium-Ion batteries that are a part of the solution must have an energy capacity under 300 Wh (watt-hours) [10].

C.3 Existing Solutions

The current design space for accessible aircraft seating solutions remains limited. One notable concept our team examined is the “Air Chair,” developed by a group at the American University of Sharjah in the UAE [11]. The Air Chair system features a motorized chair with swivel wheels and a seat that can slide directly over an aircraft seat frame, as shown in Figure C.3. Its wheels are designed to retract beneath the airplane seat structure, enabling the user to sit in a standard airplane seat and use the existing seatbelt. Initially, our group viewed this as the most promising direction. However, after further research and calculations (see Section 3.1), we concluded that the solution is less feasible than we first expected.

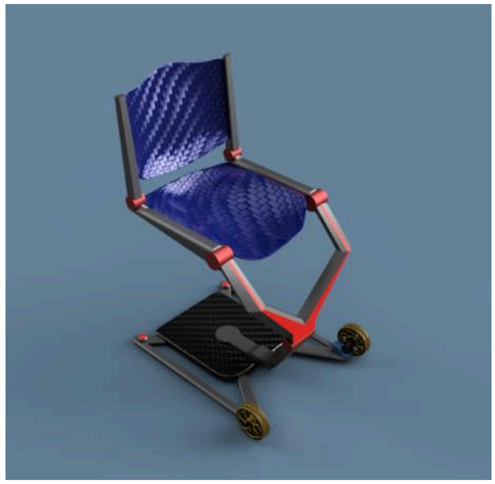


Figure C.3: The “Air Chair,” developed by a group at the American University of Sharjah in the UAE [11].

Another emerging solution is “Air4All,” an idea recently proposed by Delta. Although this system has not yet been implemented on commercial flights, Delta is currently testing and developing the concept [20]. In this design, an electric wheelchair user remains seated in their own chair throughout the flight using the system shown in Figure C.4. While Air4All initially appeared to be a compelling path, our user interviews led us to reconsider. A majority of the wheelchair users we interviewed stated that they would prefer to sit in a standard airplane seat rather than remain in their wheelchair for the duration of the flight, citing the cushioning, recline options, and higher seat backs of standard aircraft seats. Additionally, Delta has stated that the Air4All concept only accommodates users with electric wheelchairs, further limiting its applicability.

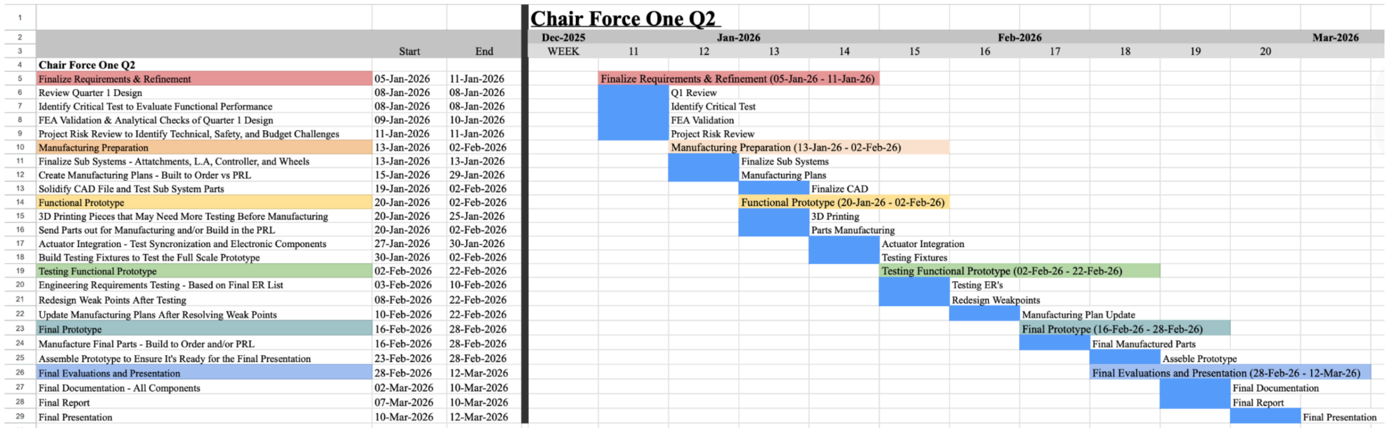
Figure C.4: A wheelchair user sitting in the Delta “Air4All” [20].

Appendix D – Action Item Log from Week 10 Design Review

Given feedback from the Week 10 Design Review, we identified the following action items to follow up on in ME170B:

1. Investigate methods to keep the smaller loose components of the folded wheelchair secured while stored in the overhead bin.
2. Determine the lateral forces acting on the wheelchair's linear actuators and confirm that the design includes an adequate factor of safety.
3. Explore options for further motorizing the wheelchair system.

Appendix E – Gantt Chart for ME170B



Appendix F – Slides Used at the Week 10 Design Review

https://docs.google.com/presentation/d/195ayxcnrVSviLLk9KX3a9xjGPKJjkeiRuBosepX1SqU/edit?usp=sharing

Appendix G – Materials from DR7 (slides, action items, handout)

https://drive.google.com/drive/folders/1YEnYGI1dgaRTSTWjutgmPAqOic2upcfN?usp=share_link

Appendix H - User and Engineering Requirements

https://docs.google.com/spreadsheets/d/16YwG5UgIMPbFnOXTSzA8XQV0glLmPv1vGL1UjqjNeUI/edit?usp=share_link

Appendix I – Expense File with Spending To Date

https://docs.google.com/spreadsheets/d/1yOKMPefFakAo4c968nWKk2WU_tDn8DQZ/edit?usp=sharing&ouid=101464848689706119542&rtpof=true&sd=true

Appendix J – I Like / I Wish Document

https://docs.google.com/spreadsheets/d/1iICp_9m5ofaa6-ltPkMipU3EkVVST482/edit?usp=sharing&ouid=101464848689706119542&rtpof=true&sd=true

Appendix K – Team Charter Document

https://docs.google.com/document/d/1gkkKugxbXCNH5EuD_kQe6CUZZFGJoIyt/edit?usp=sharing&ouid=101464848689706119542&rtpof=true&sd=true

Appendix L – References for Project Summary, Appendices B and C

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Appendix M – Detailed Calculations, Analyses, and Scripts

M.1 The Electric Chair

Link to the Python script that simulates the 180° turn and gives a collision warning while I vary the wheelchair's length and width to find the maximum safe dimensions:

https://drive.google.com/file/d/1MoegeUFMSn2oSRtsnhhOSG1jh_bgN3zB/view?usp=sharing

Additionally, the required energy capacity for general use of the AirChair was determined to be ~68 Wh, as shown in Figure M.1.

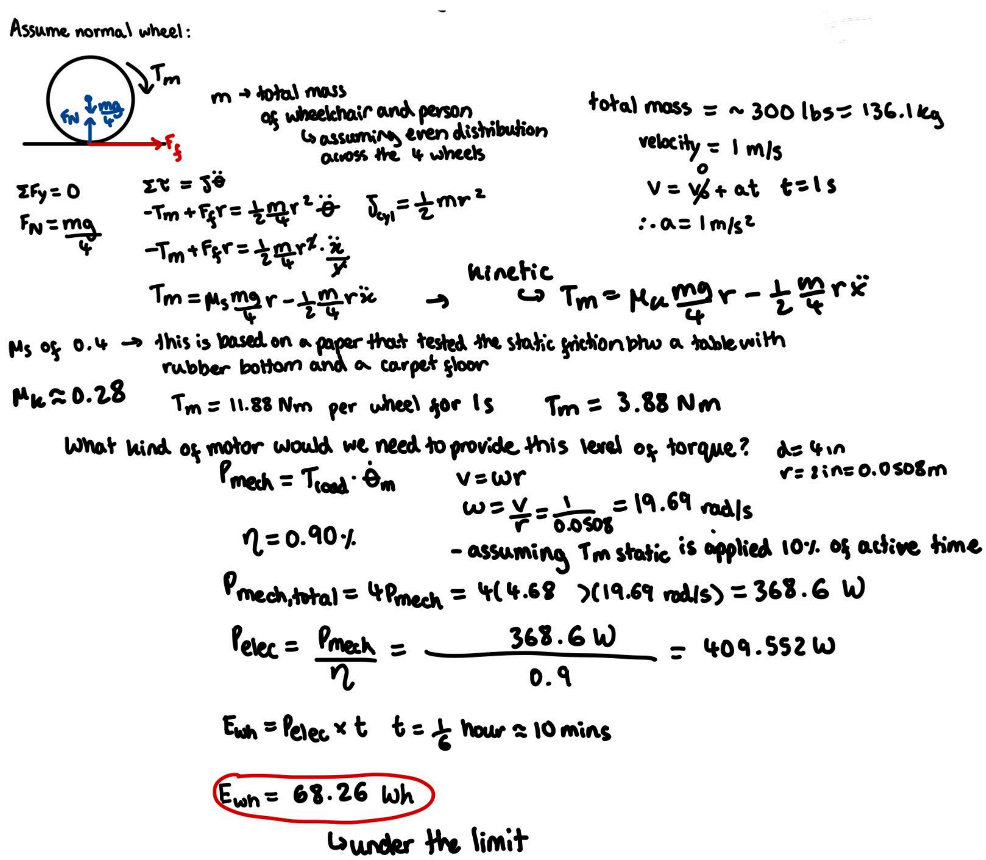

Figure M.1: Energy consumption of the AirChair due to motion. Taking into account the friction of the four mecanum wheels, and the power required to drive the four wheels for 10 minutes.

M.2 The Manual Wheelchair with Telescoping Struts

A risk identified in this concept was the potential for manufacturing tolerances or improper use of the struts to lead to the rear wheels not being directly underneath the wheelchair axle. This phenomenon is mechanical trail, and it introduces bending and shearing failure modes in the design of the wheelchair. For a full derivation of the tube sizing equations as a function of mechanical trail, assumptions followed, and the assumed values of material and wheelchair parameters, see the following link:

https://drive.google.com/file/d/1gNKUtQPrS10gIBE0BaHptX4UXnzvpdLf/view?usp=share_link

The derived equations for pin joint reaction loads, structure stresses, and the required sizing of the tubes for a specified factor of safety were implemented in the following MATLAB script:

https://drive.google.com/file/d/1f69HXQZTWHtinK5KM3IIoE4Il75y65_b/view?usp=share_link

From this script, Figure M.2 was generated to show how the outer diameters of the rear struts and the telescoping struts vary as a function of the wheel mechanical trail behind the rear wheelchair axle. The plot shows that, for 6061-T6 aluminum tubes with a thickness of 0.125 inches, a minimum outer diameter of ~0.5 inches is satisfactory for wheel trails under 2.5 inches to prevent yielding of the design due to the 300 lb weight limit.

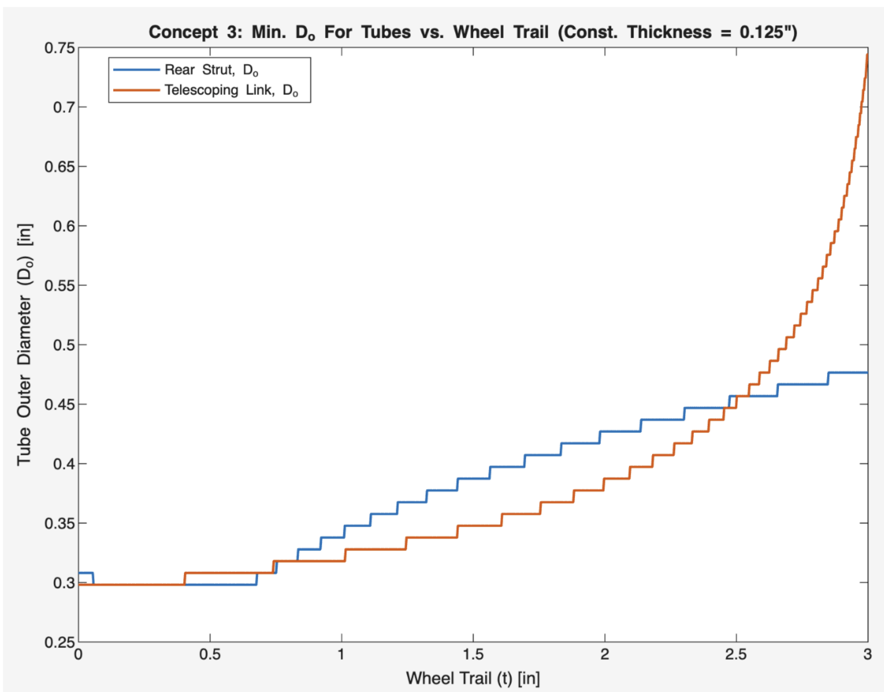

Figure M.2: The required outer diameters of the rear strut and telescoping strut to avoid yield as a function of wheel mechanical trail behind the wheelchair axle. The plot shows that for trails under 2.5 inches, an outer diameter of 0.5 inches for both of the tubes is satisfactory.