ACCESSIBLE RESTRAINTS FOR WHEELCHAIR USERS IN SHARED AUTONOMOUS VEHICLES

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EXECUTIVE SUMMARY: ACCESSIBLE RESTRAINTS

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Design Problem
For the 2.7 million wheelchair users in the U.S. [1], safe and independent transportation is often a challenge. Autonomous vehicles (AVs) represent a promising opportunity to reduce these barriers, yet current wheelchair passenger restraints remain undeveloped. *Through a sponsorship with General Motors (GM), this work seeks to develop a safe and accessible passenger restraint for wheelchair users with mobility, dexterity, and/or vision impairments.* The ultimate goal of the project is to develop a functional prototype for GM's subsidiary AV platform, the Cruise Origin.

Requirements and Specifications
Through benchmarking, stakeholder interviews, literature reviews, and consideration of standards, a robust set of requirements and specifications have been developed. The requirements broadly fit into three major categories: *safety*, *accessibility*, and *ease of integration*. Notably, we have chosen to adopt the RESNA WC-4 elective standard to inform performance metrics around restraint strength/fit. Within *accessibility*, we have created relevant specifications to address independent operation (such as ability to secure/release adorned with multiple winter coats).

Engineering Analysis and Prototype Design
Motivated by lack of existing solutions and comparative complexity, the project scope has been focused to address reach limitations, resulting in the creation of a seat belt presenter system that employs a motorized drag chain for actuation. To inform design, extensive theoretical calculations and empirical testing have been completed. Specifically, scale drag chains have been prototyped using a variety of block materials, geometries, and fabric securement methods. Following strength testing, an aluminum chain block architecture with riveted seat belt webbing has been selected. A complete presenter assembly, based around this drag chain design, has been fabricated with associated electronic controls, manufacturing plan, and materials bill ($297.55). As referenced to current benchmarks [2], the prototype design possesses comparatively longer stroke lengths for a given package size, suggesting greater accessibility and versatility.

Results and Recommendations
The prototype system successfully passes all geometric specifications pertaining to wheelchair accessibility and user physiology, and demonstrates promising results for assisting users with limited upper body mobility. However, further verification and validation are necessary to rigorously assess solution efficacy. Crucially, the drag chain and seat belt of the prototype design are prone to bind during extension, greatly reducing the current system usability. To remedy this, the expected cause of the binding has been characterized, and recommendations have been generated; namely, we suggest that future efforts investigate the relocation of the drive motor and the installation of a pivot mechanism to allow the belt opening to adjust to different pull-angles.

ACCESSIBLE RESTRAINTS FOR AUTONOMOUS VEHICLES

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ABSTRACT

Autonomous vehicles (AVs) present a significant opportunity to reduce transportation barriers for those in the disabled community, yet modern passenger restraint systems remain largely undeveloped and inaccessible. For the 2.7 million wheelchair users in the U.S., safe and independent securement in a vehicle is challenging — and all but impossible for those with compounding disabilities. Through a sponsorship with General Motors (GM), this project aims to develop an accessible restraint system for GM's subsidiary AV platform that promotes safe and independent travel for wheelchair users with impaired dexterity and/or vision.

TABLE OF CONTENTS

INTRODUCTION

Project Motivation

In the United States, nearly 1 in 4 people self-report as having a disability [3]. Of the 6 categories of disabilities recognized by the American Community Survey (ACS), ambulatory related conditions are the most prevalent [4], and an estimated 25.5 million U.S. citizens struggle with transportation directly because of a disability [5]. Modern infrastructure and transportation methods are particularly limiting to the estimated 2.7 million wheelchair users [1], [6]. As the U.S. population ages and human longevity increases, many predict that the prevalence of such disabilities is only going to increase with time [7]–[9].

The economic and social costs of this marginalization are not trivial; only 21.3% of the disabled over age 16 participate in the workforce as of 2022 [10]. The negative implications of this low employment rate are exacerbated by historically low wages and high costs of living, making those in the disabled community more than twice as likely to live in poverty [11]. If transportation barriers were eliminated, an estimated $867 billion would be added to the U.S. GDP from the newfound employment of 4.4 million disabled workers [12]. Moreover, those in the disabled community would socially benefit through better access to education, healthcare, housing, and community life [13].

Present day transportation options for the disabled are inconvenient and costly, particularly for the wheelchair community. Though the American Disabilities Act (ADA) mandates wheelchair accessible accommodations in public transportation, current systems remain cumbersome and often compromise the safety of the occupant [14]. Retrofitted passenger vehicles provide an alternative, but cost an average of $80,000 and must be operated by the user [15]. Retrofitted taxi services exist for those who cannot drive, but are also expensive and typically unreliable [16],

[17]. For wheelchair users with compounding impairments in dexterity and/or vision, cheap independent travel is all but impossible to obtain [18].

The rise of autonomous vehicles (AVs) represents a significant opportunity to reduce many of these transportation barriers. Because they do not require driver input, AVs can be independently used by those with a wide range of limiting disabilities, and physically designed to accommodate their unique needs. Furthermore, shared AV systems could operate with lower costs than current accessible taxis and rentals, while traveling more efficient routes than public transportation [19]. Despite the promise of widespread AV adoption, significant accessibility obstacles persist for wheelchair users. One of the largest remaining hurdles is the development of a safe and independently-operated wheelchair tiedown and occupant restraint system (WTORS). Though recent progress has been made in securing wheelchairs to vehicles (tiedowns) [20], safety systems to secure the user (occupant restraints) remain largely undeveloped [21], [22]. Modern wheelchair restraints often deprioritize safety through ill-fitting geometries and typically require a second person to fasten [23]. These challenges are even more demanding for wheelchair users with compounding impairments. Specifically, previous studies have shown that disproportionate barriers exist for wheelchair users with impaired dexterity [24], limited upper body mobility [25], and compromised vision [18]. Development of a safe and accessible restraint system for a wide demographic of wheelchair users would thus be a significant step towards promoting independent travel for a historically marginalized community.

Project Goal

Motivated by the aforementioned transportation barriers faced by the disabled community, General Motors (hereafter referred to as 'GM') is sponsoring this work to investigate accessible restraints for their subsidiary AV platform, the Cruise Origin. ***Specifically, this work is focused on developing an accessible passenger restraint system for wheelchair users with impaired dexterity, upper-body mobility, and/or vision in the context of a shared AV.*** The ultimate aim of this project is to develop a functional prototype that is safe, accessible, independently-operated, and accommodating to a variety of wheelchair and user dimensions.

Current Accessible Restraint Systems

To better understand the critical pain points that arise for wheelchair users when securing a restraint system, it is useful to functionally decompose the task by the sequential order of actions. Using a journeymap of wheelchair user interaction with belt-style restraint systems (informed by GM user studies [26] and stakeholder engagement [27], [28]), four major securement steps have been identified: *reaching*, *grabbing*, *routing*, and *buckling* (refer to Figure 6, p. 16). Recognition of these securement sub-functions are key to understanding the current limitations of existing solutions, and will be central in motivating project requirements and concept strategies later.

Modern wheelchair tiedown and occupant restraint systems (WTORS) rely on a complicated series of belts and adapters to fix the wheelchair and restrain the user. They are the most common type of wheelchair-focused restraints used in public transportation and retrofitted vehicles today, with major manufacturers being Q'Straint and Sure-Lok [29], [30]. Crucially, they almost always require a second person to properly secure the system — only the most capable and flexible wheelchair users can complete the full securement process (i.e. *reach/grab/route/buckle*) [31]. Modern WTORS also provide little adaptability to different user geometries, often resulting in poor belt fit that compromises user safety [32]. Such a phenomenon was substantiated in an interview with John Katona, human factors engineer at GM who is a wheelchair user with limited hand dexterity himself. Mr. Katona expressed frustration with the restraint system in his retrofitted Dodge Caravan, saying that he typically avoids using it for fear that it would actually do more harm than good in the event of a crash [27]. For a shared AV platform where safe *and* independent securement is necessary, present day WTORS remain critically undeveloped.

Wheelchairs with integrated seat belts represent another potential solution for securing occupants. These wheelchairs are typically crash tested per elective standards (refer to Relevant Standards, p. 11), and employ center locking lap belts. As such, these restraints can be highly personalized to the user and are relatively easy to secure [33]. However, these chairs still require an external shoulder belt to maximize crash safety. They also subvert the ultimate goal of universal accessibility by necessitating that users purchase a specialized wheelchair.

Notable accessibility-focused restraint products exist beyond the wheelchair context. For present benchmarking analysis, we consider seat belt presenters, buckling helpers, and belt handles (refer to Table 2, p. 6 for visuals). The general aim of these devices is to adapt a conventional 3-point belt so that it is easier to *reach*, *grab*, and/or *buckle* for users in a traditional passenger vehicle seat. It is possible that these solutions could be easily translated into the wheelchair context, but many have a narrow focus on a singular aspect of the securement process. For instance, seat belt presenters provide useful assistance for users who have difficulty *reaching* the belt, but fail to address *grabbing* or *buckling* the restraint. Additionally, no current solutions address *routing*. Thus, the ultimate takeaway of this benchmarking analysis is that no comprehensive solution exists for wheelchair users who require safe, accessible, adaptable, and independent securement.

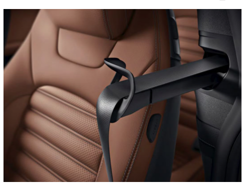
Table 1 below presents a high level summary of the different accessibility-focused occupant restraint products with comparative focus on the main user requirements considered in this work.

Table 1: High-level benchmarking of current accessibility-focused restraint products. Green = positive effect on criteria, Red = no/negative effect on criteria. Notably, no singular existing product provides a complete solution.

	***Reach* assist**	***Grab* assist**	***Route* assist**	***Buckle* assist**	**Single user**	**Promotes belt fit**	**Easy to retrofit**	**Simple**	**Reliable**
WTORS	Red	Red	Red	Red	Red	Red	Red	Red	Green
Integrated Lap Belts	Green	Red	Red	Green	Green	Green	Green	Red	Green
Seat Belt Presenters	Green	Red	Red	Red	Green	Green	Red	Red	Red
Buckling Helpers	Red	Green	Red	Green	Green	Red	Green	Green	Green
Belt Handles	Green	Green	Red	Red	Green	Red	Green	Green	Red

Table 2 (p. 6) presents more thorough commentary on the relative advantages and disadvantages of the different benchmarking solutions, with associated visuals. Ultimately, this benchmarking analysis demonstrates that none of the existing products provide a complete solution for independent and accessible wheelchair occupant securement.

Table 2: Summarized benchmarking analysis of current accessibility-focused occupant restraint products. Ultimately, no singular solution currently exists to enable safe and independent travel for wheelchair users.

	Advantages	**Disadvantages**
WTORS [34] 	● Widely used and understood ● Adaptable to different user geometries in a shared vehicle ● Uses conventional 3-point seat belt with minor modifications ● Theoretically accommodating to a variety of wheelchair geometries	● Often requires a second person to properly secure ● Difficult for users with compounding disabilities in dexterity and/or vision ● Typically deprioritizes belt fit ● Requires a wheelchair with cantilevered arms for proper routing of lap belt
Integrated Lap Belts [35] 	● Prioritize proper belt fit ● Complaint with crash loads ● Provide more accommodating buckling location ● Can be tailored to unique individual needs	● Requires users to acquire specialized wheelchair ● Only provides a lap belt; still requires eternal shoulder belt for maximum user safety ● Puts additional strain on wheelchair tiedowns in a crash
Seat Belt Presenters [36] 	● Addresses reach issue for users with low upper body mobility ● Intuitive to use ● Promotes proper belt fit by retracting into place	● Relatively high complexity / cost ● Historically unreliable / fragile [2] ● Does not address potential dexterity issues with grabbing and buckling the restraint ● Does not address proper routing of the belt in wheelchair context
Buckling Helpers [37] 	● Assists users with impaired hand dexterity ● Compatible with conventional seat belt assemblies ● Low cost and simple	● Proper alignment of the buckle can still be difficult ● Does not address reach issue for those with limited upper body mobility ● Does not address proper routing of the belt in wheelchair context
Belt Handles [38] 	● Assists users with impaired hand dexterity and limited upper body mobility ● Compatible with conventional seat belt assemblies ● Low cost and simple	● Issues with reliability [39] ● Often positioned incorrectly [39] ● Does not address buckling the restraint ● Does not address proper routing of the belt in wheelchair context

DESIGN PROCESS

Process Model

Clear identification of a design process model is an important step in framing an effective project strategy. Explicit consideration of a process framework helps to direct the course of the project, emphasizes the iterative nature of design work, and assists with keeping the project on track.

For the specific problem context considered in this work, a combination of a stage-based and problem-oriented model will be employed. Wynn and Clarkson's *Models of Designing* defines the stage-based model to be a "phase-based structure" that "lies orthogonal to the iterative problem solving process" [40]. Thus, a stage-based model consists of concrete project periods that individually involve cyclical, iterative design processes. Such a structured model is conducive to addressing the major milestone assignments that are required for this project. Meanwhile, a problem-oriented perspective is one that places emphasis on "abstraction and thorough analysis of the problem structure before generating a range of possible solutions" [40]. Due to the complexity of the design problem considered in this project, a problem-oriented approach is chosen to enable a thorough and creative exploration of the solution space.

For the purposes of this project, the relevant stages include those pictured below in Figure 1 [41]. As depicted in the block diagram, the course requirements of Mechanical Engineering 450 (MECHENG 450) have led to the creation of a stage-based, problem-oriented process model. Notably, however, the model combines the overarching stage-based framework with underlying 'activity ribbons' that reflect continual processes throughout the project progression. This combination of concrete milestones with transcendent activities is a useful mental framework to emphasize the critical processes that must persist throughout the design evolution. For these reasons, this design process model will be used to provide the general framework of this project.

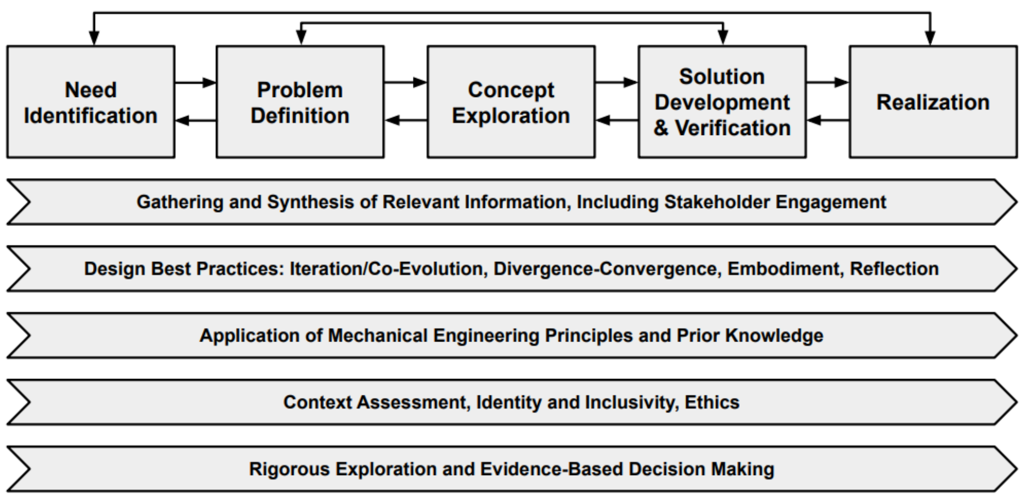


Figure 1: The stage-based, problem-oriented design process framework employed for this project [41].

This project is generally constrained to the three middle stages of the design process model depicted in Figure 1; that is, problem definition, concept exploration, and solution development and verification. Need identification has largely been accomplished by our project sponsor (GM), and thorough solution realization will likely prove out of scope for the given project timeline (discussed further in Validation Plans and Results, p. 57). Thus, the purpose of this report is to document the development of these three central process stages, which have involved a copious amount of iterative engineering analysis, prototyping, empirical testing, and sponsor communications. This recursive nature is reflected by the overarching feedback loops depicted in Figure 1. Such an explicit recognition of iteration is necessary to produce effective and rigorous solutions that continuously evolve to meet the fundamental user need.

Another useful design process for framing this project is the FDA's waterfall design process, pictured in Figure 2 [42]. This process reflects a stage-based and problem-oriented approach similar to the MECHENG 450 class framework (Figure 1), with an added emphasis on review. Such a discretized review structure will be employed through the course of our design process, and is particularly helpful in addressing our human-centric problem. Continual interactions and review by the relevant stakeholders will play a large role in driving iteration of the design.

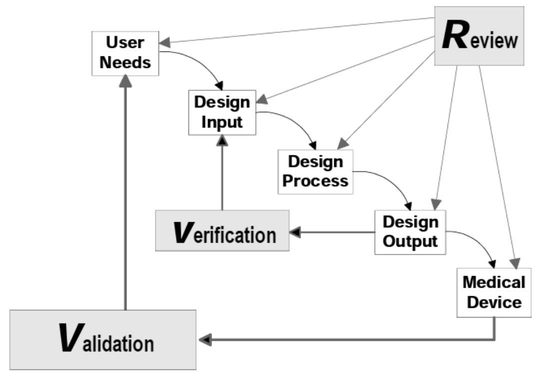


Figure 2: Waterfall design process [42].

A combination of these two frameworks will work well for this unique project context because of the broad and open-ended nature of the problem. Such a design process will emphasize thorough exploration of the solution space and continual interaction via stakeholder review.

DESIGN CONTEXT

Stakeholder Analysis

Due to the inherent social nuances surrounding our human-centric problem definition, clear identification of the relevant stakeholders is critical. Figure 3 presents the 6 types of stakeholders considered in this work, as well as their relative proximity to the problem.

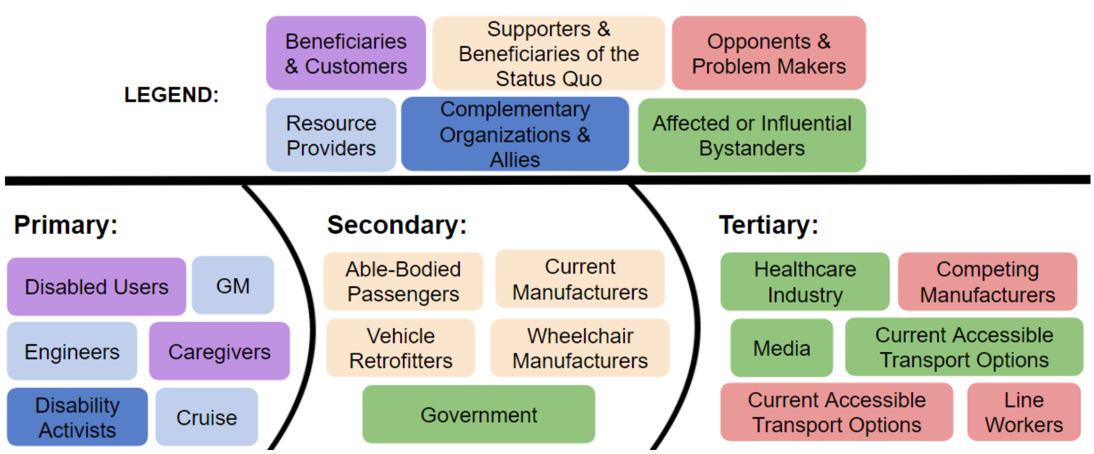


Figure 3. Stakeholder map for the accessible wheelchair restraint context considered in this work.

The primary stakeholders in this specific project include: the beneficiaries and customers (those who may benefit from the solution), the resource providers (those who give context or monetary support to achieve the solution), and complementary organizations and allies (those who may impact the engineer's ability to find a solution) [43]. The disabled users and caregivers are essential to the scope of the project, and will be essential in the verification of solutions proposed. GM, the engineers, and Cruise are providing background context and support to solve the problem. Disability activists will provide further support and useful perspective.

The secondary stakeholders in this project include: supporters and beneficiaries of the status quo (stakeholders who benefit if there is no solution created) and affected or influential bystanders (those who have no direct impact on immediate solutions now, but could have influence later) [43]. Able-bodied passengers, current manufacturers, vehicle retrofitters, and wheelchair manufacturers all support no change in the status quo — they all maintain a profit or reason to keep things the same. The government is an affected bystander who would be impacted by a solution in the accessible space; they could mandate a change for safety in autonomous vehicles.

The tertiary stakeholders in this specific project include: opponents and problem makers (stakeholders who contribute to the problem and oppose to any solutions) and affected or influential bystanders [43]. Competing manufacturers, current accessible transport options, and line workers all oppose efforts to develop a solution due to large changes in manufacturing methods or competition for profits. The healthcare industry, media, and current accessible transport options will be affected bystanders, because any solutions provided will impact the accessibility space, which all of the listed are a part of.

Overall, wheelchair users, GM, Cruise, and caregivers will constitute the prioritized group of stakeholders, as they are the direct beneficiaries of this work. It is possible that conflicting requirements emerge among these stakeholders, but it is generally anticipated that forward progress in the accessibility space is good for all. In this project scope, it is hard to rigorously consider the effects of resources, raw materials, or disposal because of the prototype nature of the concept generated in this work. However, the final (production-ready) solution will likely have a long operating lifespan (far different than a consumable product), so we do not anticipate significant negative effects surrounding disposal, manufacturing, and/or material usage.

Power Dynamics

When working on such a human-centric problem, consulting with stakeholders necessarily results in nuanced power dynamics. The engineers and the sponsor (GM) working on the project have a visible form of power over the design process that they take, and a hidden form of power over "what considerations are prioritized in the decision making process" [44]. The engineers also have an invisible form of power over the stakeholders in the way they "influence" their beliefs, "sense of self, and acceptance of the status quo" [44]. This is important to recognize because the designers of the concepts have a great deal of power over what stakeholders are included and how the problem is addressed.

Social Contexts

The goal of this project is to make transportation more accessible for wheelchair users, which ultimately has the potential for broad social impacts. As aforementioned, accessible innovations within this sector could lead to considerable advancements in employment, education, healthcare, housing, and community life for wheelchair users [13]. Everyone deserves to be able to move around, and this project hopefully generates a way of making it more accessible.

We (the team of student-engineers tasked with this project) are invested in the social impact, as is the sponsor (GM). Both we and GM rank social impact very highly, as is evident by the allocation of resources and engineers to the accessibility space [45]. Although GM is invested in the forward movement of accessible transport, it is still important to recognize their position as an industry leader that is undoubtedly profit-focused. However, they have demonstrated clear interest in prioritizing equality, which will tend to have a positive impact on the project overall.

Intellectual Property

The intellectual property of the project belongs to GM. There is potential for possible patent-filing at the end of the design process, contingent on solution efficacy and uniqueness. In such a scenario, we (the student-engineers) would be listed as inventors on the patent, with the possibility of pursuing the project beyond the scope of the class (such as implementing the design solution in more vehicles). For current intellectual property protections, there are some solutions and patents that solve a small part of the user requirements (refer to Current Accessible Restraints, p. 4). Namely, patents exist for a seat belt presenter, a belt grab handle, and a buckling assist device (patent numbers US7686338B2, US7011375B1, and US10791801B2, respectively). However there is no “best fit” solution for the problem as a whole, and the existing patent claims are relatively narrow in scope. Consequently, we do not anticipate intellectual property challenges with the final design.

Sustainability

Cruise vehicles are to be used in a rideshare context, with an anticipated lifespan of 1 million miles [46]. This promotes the sustainability aspect of the project, as they will be used by many people for an extremely long range — about five times as long as a classic vehicle [47]. Within this problem context, the manufacturing of the restraint system should not be all that dissimilar to a classic seat belt, and thus will likely not be a significant contribution to sustainability concerns.

Ethics

As four able-bodied engineers, there are inherent biases that will influence our perspective of the problem. This ethical dilemma could lead to enforcing stigmas and/or failure to analyze every facet of the problem. To manage this, it will be key to express empathy and sensitivity to the vast issues that wheelchair users face. Specifically, the use of stakeholder empathy interviews with wheelchair users and people who are well versed in the space will help, with an emphasis to allow such parties to freely explain their point(s) of view. All of the engineers working on the project have undergone bias training in other classes in the Mechanical Engineering department. The personal ethics of the engineering team, University of Michigan, and GM are all rooted in inclusivity and equality. The three parties are all striving to make solutions for all, and recognize that working in the accessibility space is highly nuanced and sensitive.

REQUIREMENTS AND SPECIFICATIONS

Relevant Standards

For traditional passenger vehicles sold in the United States, the Federal Motor Vehicle Safety Standard (FMVSS) 209 specifies important performance metrics and geometric constraints [48]. The standard provides crash compliant loads for Type 2A seat belt assemblies (the conventional 3-point architecture), as well as interaction forces for buckles (such as the maximum release force). FMVSS 209 also mandates proper fit for a standardized user distribution from 5% female to 95% male, and provides the relevant physiological dimensions. Crucially, the FMVSS 209 standard *does not apply* for vehicle occupants in wheelchairs.

For wheelchair passengers, the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) provides an elective standard that translates the FMVSS 209 into the wheelchair space. Titled the RESNA WC-4, the standard provides restraint force ratings analogous to FMVSS 209, as well as positional constraints for anchor points and proper belt fit [49]. The standard also provides testing and verification specifications for wheelchair seat belt assemblies. However, the standard does not address accessibility concerns surrounding dexterity, vision, or reach (a consequence of limited upper-body mobility).

To promote accessibility and independent use of a potential wheelchair restraint system, consideration of reach, dexterity, and vision impairments are crucial. The American Disabilities Act (ADA) provides useful dimensional constraints for placing objects within accommodating reach of wheelchair users [50]. Standards for vision, however, prove more elusive. In the context of web development, the World Wide Web Consortium (W3C) specifies a minimum color contrast ratio for making objects visually differentiated from their background for those with impaired sight [51]. Furthermore, the LogMAR visual acuity scale can be used to inform object sizing based on relative percentages of one’s field of view [52]. Unfortunately, no relevant standards could be found to address impaired dexterity.

These standards — in conjunction with relevant stakeholder interviews (such as wheelchair users [27], disability researchers [28], and GM/Cruise engineers [53], [54]) — are used to inform the requirements and specifications presented next.

User Requirements and Engineering Specifications

To ensure that future solution strategies properly reflect the ultimate stakeholder needs for this unique problem context, a wide scope of user requirements are presently considered. Broadly, these requirements can be categories into those pertaining to s*afety, accessibility,* and *ease of integration*. These requirements — along with their relevant sub-requirements/specifications — are comprehensively provided in Table 3. To constitute a safe restraint system, the restraint must fit properly and the belt/buckle must be of proper strength for a crash scenario. As previously discussed (see Relevant Standards, p. 11), robust standards exist to specify these geometric constraints and force loads: FMVSS 209 [48] and RESNA WC-4 [49]. Specifically, FMVSS 209 is referenced to inform the tensile strength requirements for the restraint belts and buckle for crash testing purposes. RESNA WC-4 is then used to specify proper belt fit for wheelchair users, per Table 3 and Figure 4 presented to the right.

Table 3: RESNA WC-4 belt fit metrics [49], used in conjunction with Figure 4.

Occupant Size	N1 [mm]	N2 [mm]	SR [mm]
6-year old	52	91	273
10-year old	58	101	325
small female	66	109	353
midsize male	76	127	406
large male	81	135	432

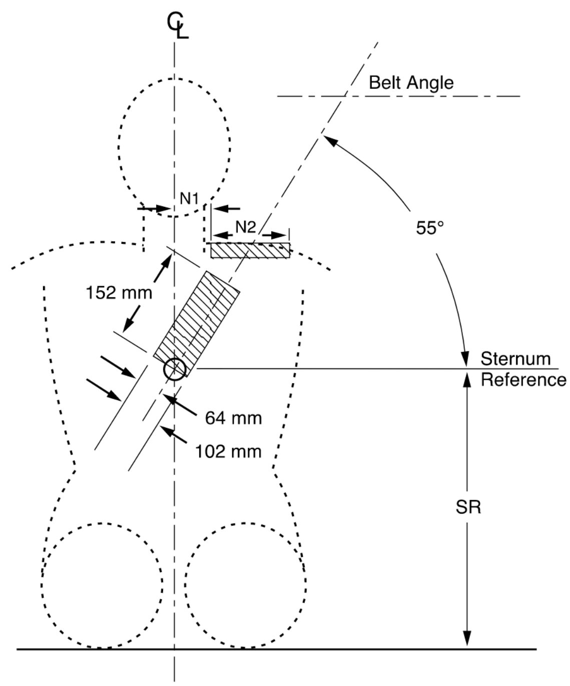


Figure 4: Visual of RESNA WC-4 belt fit metrics [49], with acceptable ranges provided in Table 3.

As ease of use is of paramount concern, mandating accessibility is a high priority. Specifically, we want to make sure that the prototype restraint system is intuitive to use and easy to manipulate (i.e. *reach/grab/ route/buckle*). This category of requirements is particularly relevant for the shared AV context considered in this work, as users must be able to secure themselves independently. A combination of standards, stakeholder interviews, and benchmarking measurements are employed to generate the associated specifications. For instance, ADA Section 4.2 [50] is referenced to define appropriate reach dimensions for wheelchair users, shown in Figure 5. Relevant visual standards such as W3C [51] and LogMAR [52] are used to inform color and sizing, respectively. Benchmarking measurements are considered for an existing Cadillac seat belt assembly to inform improvements in accessibility. Specifically, key restraint behavior metrics such as belt retraction force and buckle securement/release force are referenced to empirical measurements via a simple hand held force gauge, and used to motivate maximum anticipated forces for later solution strategies. The physical dimensions of the buckle receptacle guide ramps are also presented (as measured by digital calipers) to capture the ease of alignment and thus the overall ease of buckling. Similar measurements will be crucial in later solution development work to verify that the chosen prototype design successfully addresses these key accessibility needs as compared to existing assemblies. Lastly, stakeholder interviews with wheelchair users [27] and GM [53] are used to specify intuitiveness in terms of metrics like time and steps.

Finally, ease of integration requirements are considered such as compatibility with existing wheelchairs/vehicles, as well as general design metrics like cost, durability, and ease of assembly. To ensure that the restraint system is compatible with a wide range of wheelchair geometries, a maximum wheelchair volume is considered and referenced to the bulky wheelchairs used in hospitals for patient transport [55]. We also mandate compatibility with wheelchairs that have closed arm rests; a common geometry that makes proper routing of the lap belt difficult. Another notable requirement in the functional category is social inertness, or how inconspicuous the design is to onlookers. This requirement surfaced through meetings with the project sponsor (GM) [53] as well as interviews with wheelchair users [27], and reflects a common user sentiment to not want to be 'flagged' as disabled/different in a public context. These requirements and specifications are summarized in Table 4.

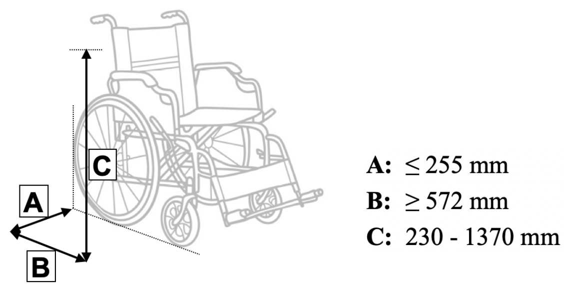


Figure 5: ADA compliant reach dimensions [50].

Table 4: Requirements and specifications, as informed by ***standards***, ***stakeholders***, and ***measurements***.

REQUIREMENT		SPECIFICATION	JUSTIFICATION
Safe	**Proper belt fitment**	· Compatible with 5% female to 95% male range: · Sitting height: **(785 - 965) mm** · Waist: **(599 - 1080) mm** · Chest depth: **(190 - 267) mm** · Compatible belt fit per **Figure 4** (p. 12): · Belt width ≥ **46 mm**	*FMVSS 209 Standard* *RESNA WC-4 Standard*
	Compliant belt strength	· Compliant with Type 2A architecture tensile loads: · ≥ **22,241 N** for pelvic belt restraint · ≥ **17,793 N** for upper torso belt restraint	*FMVSS 209 Standard*
	Compliant buckle strength	· Compliant with loads of: · ≥ **40,043 N** in tension · ≥ **1,779 N** in compression · False latching release force ≤ **22 N**	*FMVSS 209 Standard*

Accessible	**Intuitive**	· Time to secure ≤ **1 minute** · Steps ≤ **6** · Can be secured **independently** · 5-point Likert scale score ≥ **4.0***	*Stakeholder sentiment* *GM requirement*
	Easy to reach and pull restraint	· Grab point dimensions (refer to Figure 5, p. 13): · A: ≤ **255 mm** · B: ≥ **572 mm** (beyond 95% male frontal plane) · C: **(230 - 1370) mm** · Belt retraction force ≤ **8 N**	*ADA 4.2 Standard* *Benchmarking measurement*
	Easy to buckle and unbuckle	· Able to be secured / released with oven mitts · Release force ≤ **21 N** · Insertion force ≤ **52 N** · Buckle guide ramp ≥ **10 mm** fore/aft, ≥ **5 mm** side · 5-point Likert scale score ≥ **4.0***	*Benchmarking measurement* *Best estimate*
	Easy to see	· Visual color contrast ratio of **4.5:1** · **50 minutes of arc** of visual field of view · 5-point Likert scale score ≥ **4.0***	*W3C 1.4.3 Standard* *LogMAR Standard* *Best estimate*
Easy to Integrate	**Compatible with existing wheelchairs**	· Accommodating to maximum wheelchair size of: · (L x W x H) = **(1068 x 712 x 915) mm** · ***Not necessarily cantilevered arms*** · Seat height: **(430 - 510) mm**	*Benchmarking measurement* *GM requirement*
	Compatible with existing vehicles	· Maximum footprint of: · (L x W x H) = **(1100 x 810 x 1060) mm**	*Benchmarking measurement*
	Durable	· Ability to withstand **50,000 cycles****	*FMVSS 209 Standard*
	Socially inert	· 5-point Likert scale score ≥ **4.0***	*Stakeholder sentiment*
	Cost	· ≤ **200%** of traditional seat belt assembly cost	*GM requirement*
	Ease of assembly	· ≤ **200%** of traditional seat belt assembly steps	*GM requirement*
	Comfortable	· Inner belt intrusion ≤ **10 mm**	*Best estimate*

** Likert studies planned to be administered to GM Able, discussed further later (p. 58)*
*** Outside scope of work*

Relative Importance of User Requirements

As motivated previously, the ultimate goal of this project is to design a safe and accessible vehicle restraint for wheelchair users with compounding disabilities. Maximum priority is therefore placed on fulfilling the requirements surrounding safety and accessibility. Though the RESNA WC-4 wheelchair restraint standard is elective and not federally mandated, user safety is clearly of paramount concern and will be considered a necessity. Additionally, independent operability and a high ease of use are necessities for the prospective shared AV setting. This focus on promoting accessibility will be a central motivator for subsequent concept generation, and has led to the selection of a multifaceted design that addresses the compounding impairments considered in this work (refer to Proposed Concept Design, p. 25). However, as will be discussed later, the project scope has narrowed to primarily focus on addressing user reach, as solutions in this space are comparatively less developed and more complex.

In contrast, the ease of implementation requirements generally represent 'best wishes.' For instance, the restraint system will ideally be compatible with a wide range of wheelchair geometries, but potential incompatibility with certain wheelchairs is far less detrimental than compromises in safety. Similar logic applies for other functional requirements such as compatibility with existing vehicles. This requirement was suggested by GM to enable integration into their other passenger vehicle platforms [53], but is not necessary to achieve the central project goal. Finally, requirements like cost and ease of assembly are certainly important to ensure economic project viability, but there is likely some flexibility within those domains.

Prospective Verification Strategies

Following construction of a functional prototype, many of these specifications lend themselves well to verification via straightforward measurements — particularly those concerning dimensions, forces, and time. Visual metrics (such as color contrast ratio and relative field of view) will be handled through photography and digital image processing. To obtain meaningful Likert scale results, later discuss administering questionnaires to GM's disabled organization, GM Able. This will likely yield the most appropriate sample of our target demographic. More intractable requirements such as cost and ease of assembly are specified in reference to existing seat belt assemblies to aid in future verification via simple comparison. Notably, however, cycle fatigue testing of restraint hardware remains out of scope due to the scale of cycles necessary.

Commentary on Scope of Requirements

Through our broad consideration of requirements, we have generated a rather rigorous set of specifications that might appear intractable for a short operating timeline. It is important to mention that future solution strategies might negate the need to consider the full scope of requirements. For instance, if a selected concept involves making external modifications to an existing seat belt assembly (as is discussed in Proposed Concept Design, p. 25), minimal effort will be required to verify complaint crash strength because that work will have been previously completed. However — to enable a complete understanding of the problem space — a thorough perspective on user requirements has proven useful.

CONCEPT GENERATION

To generate relevant and effective concepts, a broad perspective of the solution space is assumed, then systematically narrowed down to a targeted design space. The problem is then functionally decomposed based on user actions, and the subsequent concepts are combined based on compatibility matrices to generate total solutions. Concept trees are used throughout the generation process to structure the solution space, visualize the breadth of consideration, and motivate areas for further ideation.

General Methodology and Process Strategy

To aid rigorous exploration of the solution space and promote identification of an appropriate solution strategy, a systematic generation process is presently discussed. First, a broad perspective is assumed to foster divergent thinking and encourage an exhaustive consideration of the relevant concept spaces. Here, untraditional and novel ways of restraining vehicle occupants are presented and evaluated. This wide analysis is then narrowed down to a specific solution space for further investigation by considering the overarching project requirements and timeline. Specifically, the conceptual space is narrowed to belt-style restraints (refer to Broad Consideration of Solution Space, p. 17).

With a focused solution space identified around belt-style restraints, further ideation is necessary to develop refined concepts that cater to the unique problem scenario considered in this work. To aid this generation process, the problem is functionally decomposed based on the sequence of user actions [56]. Specifically, we consider a high-level journey map of how a representative wheelchair user interacts with a current seat belt assembly, and use the discretized sequence of actions as a basis for targeted ideation. Figure 6 presents the resulting journey map and thus the four major action domains considered for subsequent concept generation (i.e. *reach/grab/route/buckle*). This subdivision of the wheelchair user experience is informed by user studies conducted by GM [26], as well as our own engagement with relevant stakeholders [27], [28]. Notably, *routing* reflects the process of threading the restraint through the wheelchair armrests so that it properly seats on the user's lap.

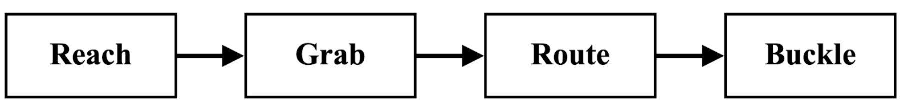


Figure 6: High-level journey map of wheelchair user interaction with belt-style restraint systems. These sub-functions represent the major domains for subsequent ideation.

With ideas generated within each of the four sub-functions presented in Figure 6, a systematic method is then necessary to combine the discrete concepts into complete solutions. However — given the depth of ideas generated within each sub-function — a purely combinatorial approach would lead to an intractable amount of solutions. Instead, a progressive approach is taken. Sub-functions are sequentially combined and the resulting combinations are broadly evaluated based on compatibility. Importantly, the order of this process is carefully chosen to prioritize any potential coupling between sub-functions. Figure 7 depicts this sequential approach (p. 17).

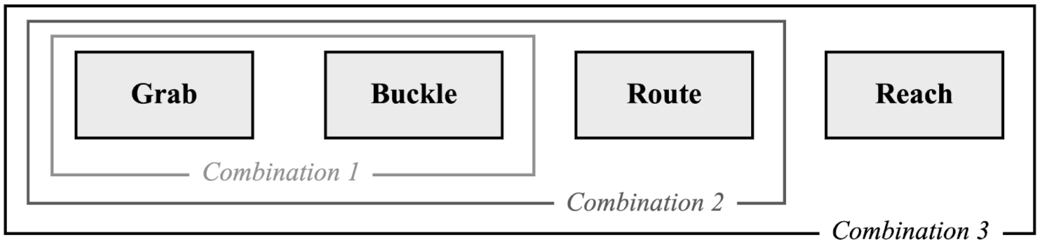


Figure 7: Sequential combination of sub-functions to combine discrete ideas into total concepts. Order reflects prioritization on potential coupling between sub-functions.

As illustrated in Figure 7, the grab and buckle sub-functions are combined first because they are thought to be the most coupled; both involve fine motor control and manipulation of the restraint, so solutions in one domain will likely impact the other. Routing is largely decoupled from grabbing and buckling, and is combined next. Finally, reach is added. As discussed in product benchmarking (Current Accessible Restraint Systems, p. 4), present solutions that aim to address reach remain far less developed than products focused on the other sub-functions such as grabbing or bucking. A novel and effective solution within the reach domain will also likely involve more complexity and analysis than those within buckling/grabbing/routing. For these reasons, a comparatively high effort is placed on ideating within the reach sub-function, and these concepts are consequently combined last.

Thus, to reiterate, the general concept generation strategy is to ideate within each of the four sub-functions (i.e. *reach/grab/route/buckle*), prune the resulting concept trees, then sequentially combine sub-functions based on compatibility.

Broad Consideration of Solution Space

As aforementioned, a broad perspective is initially assumed for concept generation to encourage divergent thinking and the consideration of novel ideas. It is during this phase of conceptual development that we explore the untraditional — and potentially infeasible — solution strategies for restraining wheelchair users in a passenger vehicle setting. Figure 8 presents the resulting concept tree. Notably, the conceptual strategies fall within one of three categories: active, passive, or a combination of both active and passive elements. In this context, we consider 'active' to indicate some level of automated actuation/securement, while 'passive' systems require the user to operate the restraint. Within the active category, undeveloped and untraditional ideas involving inflatables and electromagnets are suggested, and additional reference is made to existing restraint solutions in other contexts (i.e. roller coaster harnesses). Within the passive category, we consider solutions that are attached to the wheelchair (such as integrated belts), or attached to the vehicle (such as traditional belt systems). Finally, the combination category incorporates some level of automation with user input, such as moving anchor points or active belt elements.

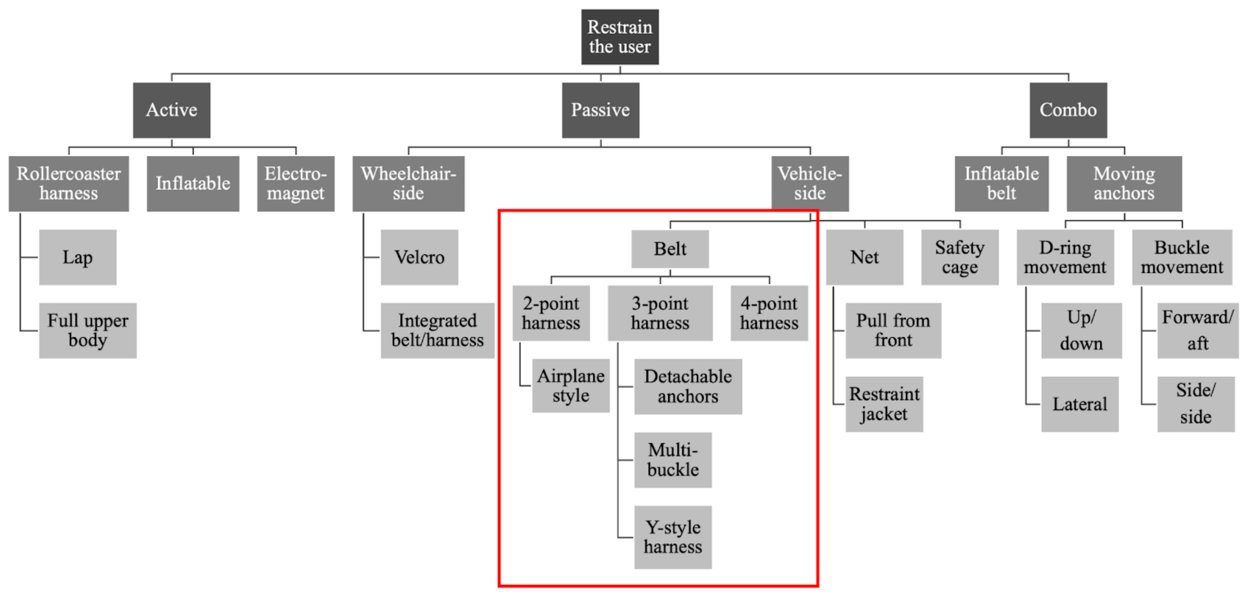


Figure 8: Conceptual mapping of broad generation perspective for restraining wheelchair users in a passenger vehicle context, with a subsequent focus on belt-style systems.

To provide a concrete solution space for further conceptual ideation and refinement, the broad conceptual tree is narrowed to belt-style systems. This decision is motivated by a number of relevant factors. Ultimately, belt-style systems are the most prevalent method for securing occupants in passenger vehicles today [57], [58]. As a consequence of this ubiquity, a robust history of safety testing and rigorous standards exists specifically for belt-style restraints (such as those discussed in Relevant Standards, p. 11), ensuring confidence that a solution within this domain could be properly enacted and safe. Furthermore, this well-understood category aids the development of a functional solution in our short operating timeline by not only decreasing novelty and complexity, but by increasing the availability of parts — seat belt retractors, buckles, and webbing can be easily and affordably sourced [59]. Because of these advantages in feasibility and design wisdom, our subsequent concept generation and ideation will therefore focus specifically on belt-style restraint systems.

Sequential Combination of Sub-Functions

As discussed previously (General Methodology and Process Strategy, p. 16), concept generation within the belt-style restraint domain begins with a functional decomposition of the problem by the sequence of user actions. Concepts within these sub-functions (namely, *reach/grab/route/buckle*) are then sequentially combined based on coupling to generate total solutions (Figure 7, p. 17). As such, we begin our discussion with the first sub-combination: grabbing and buckling.

Grabbing and Buckling. Because of the shared reliance on user dexterity and need to manipulate the restraint, grabbing and buckling are highly coupled. Additionally, as elucidated through product benchmarking (Current Accessible Restraint Systems, p. 4), solutions to address these two sub-functions are fairly developed and successful (though very narrow in focus). Thus — though we presently generate concepts for these functions — the underlying motivation is to heavily rely on the success of existing solutions. As will be further discussed later, these components of the final design strategy will remain largely demonstrative in nature (outside of future engineering scrutiny) because of their relative simplicity and maturity.

Nonetheless, Figure 9 presents a conceptual tree for grab-related solutions. Though a variety of ideas are considered on both the belt-side and user-side of the problem, the concepts are quickly narrowed down to the open-end handle and sliding strap (as indicated in Figure 9 by the red outlines). These two strategies are selected because developed solutions within these categories exist on the market today and have found appropriate levels of success [37], [38].

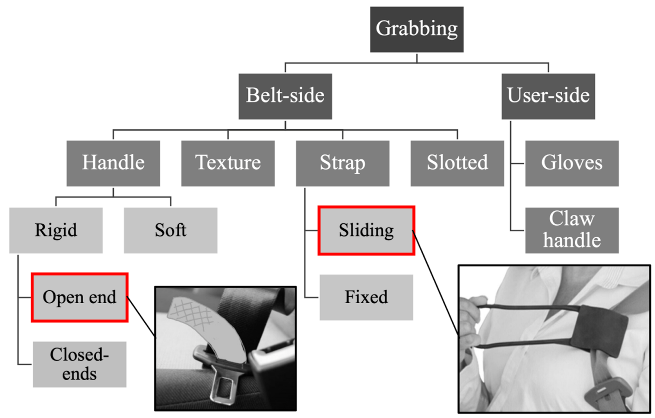


Figure 9: *Grabbing* concept tree. Images from [60], [61].

Figure 10 depicts a similar concept tree for the buckling sub-function. Broadly, ideas in this domain can be described as 'novel' or 'traditional,' with concepts in the former category representing ideas that are not well developed in industry. Pruning of the tree to the four highlighted concepts is motivated by high-level feasibility considerations as well as stakeholder input. For instance, the novel concepts are generally dismissed because of their need to thoroughly redesign the buckling mechanism (a task that would likely prove intractable in this project's short operating timeline if safety standards are to be met). Notably, a magnetic approach could be ancillary to an existing buckle assembly, and is therefore not yet set aside. Within the traditional category, solutions are generally considered to be favorable because of their ease of integration and relative maturity. Here, only 'button' buckles are dismissed (referring to the traditional style used in passenger vehicles where the user must press on a small button to release the restraint) because they require considerable hand dexterity and thus remain inaccessible to our target user group [62].

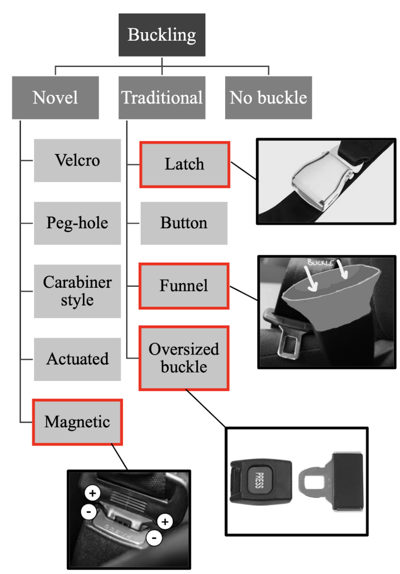


Figure 10: *Buckling* concept tree. Images from [60], [63]–[65].

These discrete concepts are now combined with a compatibility matrix to evaluate any potential synergies between ideas, depicted in Table 5 (p. 20). Here, plus signs (+) represent synergistic combinations, zeroes (0) describe possible yet unremarkable compatibility, and minus signs (-) denote conflicting combinations. Notably, the latch style design is considered incompatible with both the handle or strap concepts because it requires manipulation of both ends of the buckle system (i.e. both the latch plate and the receptacle), while other concepts have a fixed side and thus only require a single handle or strap. Compared to a rigid handle, the strap concept allows comparatively less alignment and manipulation, and thus is considered to have synergy only with the magnetic buckle style. To help narrow the solution space and avoid a runaway swell of combinatorial concepts, only the three synergistic combinations identified in Table 5 will be considered moving forwards.

Table 5: Compatibility matrix for grab and buckle concepts.

	Handle	Strap
Latch	-	-
Magnetic	0	+
Funnel	+	-
Oversize	+	0

Routing. As previously described, 'routing' the belt consists of strategically threading the belt webbing through the armrests of the wheelchair assembly so that the belt lies properly on the occupant (Figure 4, p. 12). Unfortunately, such a task is topologically impossible for closed armrest wheelchairs when using a traditional 3-point assembly. Consequently, ideas in this domain either compromise the safety of the occupant through poor fit, involve multiple buckles, or require a more novel approach to restraint systems. These concepts are illustrated in Figure 11.

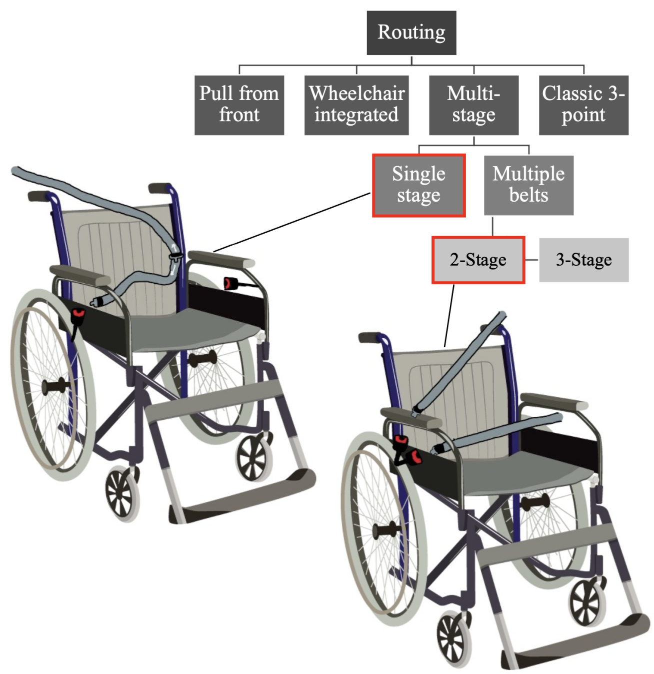


Figure 11: *Routing* concept tree. Images modified from [66].

Compared to the other solution strategies, a multi-stage approach is favored because it prioritizes occupant safety, can leverage tested hardware, and promote accessibility across wheelchair geometries. Of the multi-stage configurations, a 3-stage design (with a center latching lap belt) is disregarded because of its increased complexity without any notable advantage.

These routing strategies can now be combined and evaluated based on compatibility with those of the buckling and routing sub-functions. Table 6 presents this cross-combination. Notably, only the single belt with oversized grab handles is discounted. This is because the single belt configuration requires that both latch plates

Table 6: Compatibility matrix with inclusion of routing concepts.

	Strap	Handle	
	Magnetic	Funnel	Oversize
Single stage	+	+	-
2-Stage	+	+	+

retract onto a single overhead anchor point, so multiple oversized latch plates in one location may be unwieldy and difficult to use. Thus, five synergistic combinations remain.

Reaching. Because of the lack of existing solutions, as well as the comparatively high complexity, the reach domain represents the central focus of this ideation process. Consequently, a more rigorous breadth and depth of potential solutions are presently considered compared to the other sub-functions, as depicted in Figure 12.

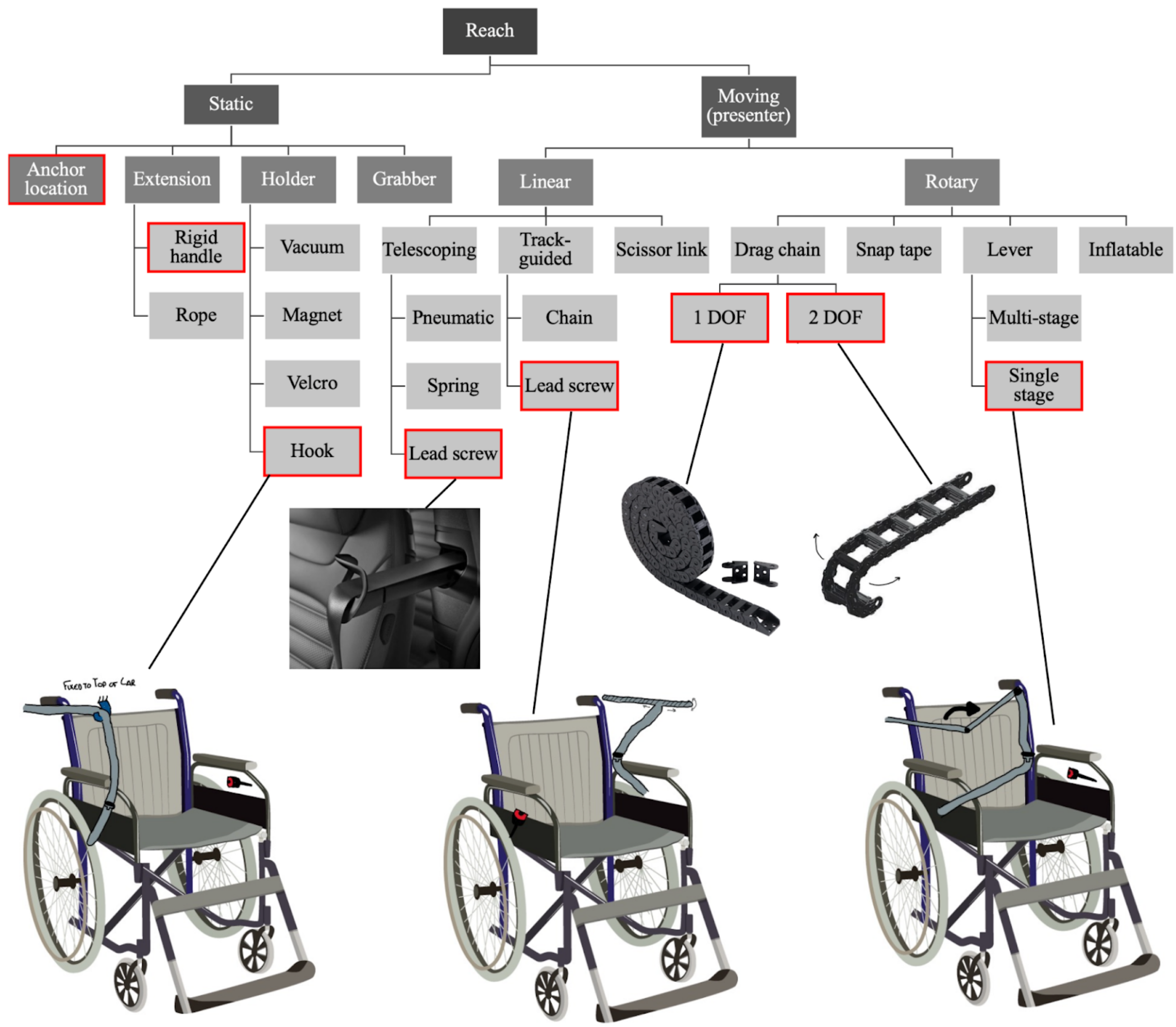


Figure 12: *Reach* concept tree, broadly categorized as static or moving strategies. Images from [36], [66]–[68].

These concepts are broadly classified as 'static' and' moving', with the latter category comprising some level of automated movement that 'presents' the seat belt to the occupant. Within the static category, we propose solutions such as moving the anchor location to an easier to reach spot, adding physical extensions on the belt that make it easier for the user to reach, temporarily holding the belt at a fixed location that is nearer the user, or providing the user with some sort of grabbing mechanism that augments their reach capabilities. Within the moving classification, we consider strategies that advance in a linear fashion (such as telescoping, track-guided, or scissor links) and those that rotate (such as drag chains and levers). Drag chains — a less familiar mechanism than many of the others suggested in Figure 12 — are a series of links that are uniquely rigid in one direction, and therefore allow a spool of links to translate a rotary motion into a linear one. They are most commonly used in a passive method for cable routing in industrial machines and equipment [69], but some exist as actuators [70].

Similarly to the other sub-functions, this concept tree is pruned primarily through feasibility considerations (i.e. product benchmarking and novelty) as well as stakeholder engagement (with GM and relevant wheelchair users). Within the static category, three concepts are retained: moving the anchor location, adding a rigid handle, and holding the belt with a hook. The rigid handle has emerged as a semi-successful benchmark [37], while the hook-holder is believed to be a simple/easily implemented concept. The changing of the anchor point location — likely a significant compromise in user safety — is retained solely as a baseline for comparison and improvement. Within the moving category, five concepts are retained: lead-screw telescoping, lead-screw track-guide, single-stage lever, and a 1 or 2 degree of freedom drag chain. The telescoping, track-guided, and lever style presenters are kept due to the presence of notable benchmarks [20], [36], [71] as well as sponsor sentiment [72]. The drag chain presenters — an idea proposed by GM — are retained due to their prospective ability to exist in compact form factors, and thus be comparatively easier to integrate into existing vehicle platforms.

Table 7 presents the final compatibility matrix with the inclusion of the selected reach concepts. Thus, combinations here represent total solutions that address each of the four sub-functions previously identified (i.e. *reach/grab/route/buckle*). Notably, the 2-stage routing concepts are widely considered to be incompatible with the active presenting element (telescoping through lever) because the 2-stage configuration requires two separate presenting locations, and thus double the complexity. As a result of this final compatibility analysis, 17 synergistic total combinations are identified.

Table 7: Final compatibility matrix including reach concepts.

	Single		**2-Stage**		
	Magnetic Strap	**Funnel Handle**	**Magnetic Strap**	**Funnel Handle**	**Oversize Handle**
Anchor location	+	+	0	0	0
Rigid extension	-	+	-	+	+
Hook holder	+	-	+	-	-
Telescoping	+	+	0	0	0
Track-guided	+	+	0	0	0
Drag chain (1 DOF)	+	+	-	-	-
Drag chain (2 DOF)	+	+	-	-	-
Lever	+	+	-	-	-

In summary, this process of sequential ideation, pruning, and combination of the four distinct user sub-functions (reach/grab/route/buckle) has enabled the generation of 17 well-developed and promising solution candidates that broadly rely on belt-style restraints.

CONCEPT SELECTION

Pugh Matrix Analysis

To narrow down to a singular solution strategy, a Pugh matrix is presently employed to systematically rank the 17 unique concept candidates. Table 8 depicts the resulting matrix.

Table 8: Pugh matrix used for systematic downselection. Following objective scoring, a single belt with grab handles and funnel guided buckles with a 1 or 2 degree of freedom drag chain presenter is selected.

	routing		Single														2-Stage		
	grabbing		Strap							Handle							Strap	Handle	
	buckling		Magnetic							Funnel							Magnetic	Funnel	Oversize
	reaching	Weights	Anchor location	Hook holder	Telescoping	Track-guided	Drag chain (1 DOF)	Drag chain (2 DOF)	Single lever	Anchor location	Rigid extension	Telescoping	Track-guided	Drag chain (1 DOF)	Drag chain (2 DOF)	Single lever	Hook holder	Rigid extension	Rigid extension
Safety	Belt fit	9	1	6	9	9	9	9	6	1	6	9	9	9	9	6	6	3	3
	Belt strength	9	6	6	6	6	6	6	6	6	6	6	6	6	6	6	9	9	9
	Buckle strength	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	Securement risk	7	6	6	6	6	6	6	6	9	9	9	9	9	9	9	6	6	6
Accessible	Reach	9	3	3	6	6	6	9	6	3	3	6	6	6	9	6	3	3	3
	Pull	6	9	9	9	9	9	9	9	6	6	6	6	6	6	6	9	6	6
	Grab	8	6	6	6	6	6	6	6	9	9	9	9	9	9	9	6	9	9
	Manipulate	8	6	6	6	6	6	6	6	9	9	9	9	9	9	9	6	9	6
Ease of Integration: **Production**	Part maturity	5	9	9	3	6	3	3	6	9	9	3	6	3	3	6	9	9	9
	Servicability	7	9	9	1	3	6	6	6	9	9	1	3	6	6	6	9	9	9
	Aesthetics	4	6	6	6	1	6	6	3	6	6	6	1	6	6	3	6	6	6
	Durability	8	9	9	3	9	9	9	9	9	9	3	9	9	9	9	9	9	9
	Component cost	4	9	9	3	6	6	6	6	9	9	3	6	6	6	6	9	9	9
Ease of Integration: **Installation**	Complexity	6	9	9	3	6	9	6	6	9	9	3	6	9	6	6	9	9	9
	Adaptability	5	1	3	3	3	6	6	6	1	6	3	3	6	6	6	3	6	6
	Installation cost	3	9	9	1	3	6	6	6	9	9	1	3	6	6	6	9	9	9
	Packagability	7	9	9	3	3	6	6	6	9	9	3	3	9	6	6	9	9	9
Prototyping	Prototype cost	4	9	9	3	3	6	6	3	9	9	3	3	6	6	3	9	9	9
	Part availability	6	6	6	3	6	6	6	6	6	6	3	6	6	6	6	6	6	6
	Time to build	7	9	9	3	3	3	3	3	9	9	3	3	3	3	3	9	9	9
	Aesthetics	1	6	6	9	3	9	9	3	6	6	9	3	9	9	3	6	6	3
	Reliability	1	9	9	6	6	6	6	6	9	9	6	6	6	6	6	9	9	9
	Testability	7	3	3	6	6	6	6	6	3	3	6	6	6	6	6	3	3	3
Intuitiveness	Time/steps	4	6	3	9	9	9	9	9	6	3	9	9	9	9	9	3	6	6
	Familiarity	6	9	6	9	9	9	9	6	9	6	9	9	9	9	6	6	6	6
	Visibility	2	6	6	9	9	9	9	9	6	3	9	9	9	9	9	6	3	6
User perception	Comfort/intrusivity	8	9	6	9	6	9	9	6	6	1	6	3	6	6	3	6	1	1
	Ride enjoyment	1	6	6	9	3	9	9	6	6	6	9	3	9	9	6	6	6	6
	Social inertness	4	9	9	9	6	9	9	6	9	9	9	6	9	9	6	9	9	9
	Routine ease	3	9	3	9	9	9	9	9	9	3	9	9	9	9	9	3	3	3
	Total	168	1154	1137	961	1024	1173	1182	1056	1181	1157	988	1051	1221	1209	1083	1164	1148	1127
	Total Grade	1512	0.763	0.752	0.636	0.677	0.776	0.782	0.698	0.781	0.765	0.653	0.695	0.808	0.800	0.72	0.769841	0.7593	0.74537

The various solution candidates are organized along the top in a hierarchical structure denoting the constituent concept to address each sub-function. Along the left hand size is a rigorous list of metrics that have been carefully selected to represent critical points of comparison. Notably, the key requirements identified for the project (Table 4, p. 13) are represented and prioritized: specifically *safety*, *accessibility*, and *ease of integration* (reflected in production and installation). Important metrics are also defined around solution prototyping to reflect the considerations of our unique project timeline (such as prototyping cost, part availability, and time to build). Finally, additional user-focused metrics such as intuitiveness and user perception are considered to provide further emphasis upon the project's overarching goal of accessibility and ease of use.

The weights in the Pugh matrix are used to rank the importance of each sub-metric on a scale of 1 (low) to 9 (high), and were determined through user studies conducted by GM [72], engineering consultation provided by GM [26], [54], and reflection on our own engagement with wheelchair users and disability researchers [27], [28]. To fill out the matrix, candidate concepts are objectively ranked on a discretized scale of 1, 3, 6, or 9, with a score of 9 representing an exceptional ability of the concept to meet the associated sub-requirement. These scores are colored to visually aid in recognizing regions of particular strength or weakness.

Upon completion and tallying of the scores, a number of the candidate concepts emerge as potentially rather strong solutions (reflected in the rankings along the bottom of Table 8, p. 23). This is likely a consequence of the aggressive pruning employed throughout our concept generation process, wherein many of the weaker and less feasible strategies were previously filtered out. Despite this though, two solutions do emerge among the rest: single stage belts with grab handles and funnel buckles with a 1 or 2 degree of freedom drag chain presenter. If we compare these concepts to some of the other high-scoring ideas in the matrix, we can see that they are relatively weak in the metrics around production, installation, and prototyping. This is ultimately caused by the comparatively high complexity and novelty of the drag chain presenter, which will require more engineering rigor and analysis to properly realize. In contrast, the solutions that involve static reach components (such as the 2-stage strategies along the right-hand side of Table 8) perform rather well in these metrics because of their relative simplicity. However — as embodied by the dense green regions within the highlighted box in Table 8 — the two selected drag chain concepts excel in the user-focused metrics such as safety, accessibility, intuitiveness, and user perception. As discussed previously when outlining the project's requirements and specifications (Table 4, p. 13), concerns around safety and accessibility represent the fundamental goal of this work. We therefore feel confident moving forward with these two selected concepts because they prioritize the solution characteristics we are most concerned with addressing.

In discussion, two concepts were selected for future development: single stage belts with grab handles and funnel buckles with a 1 or 2 degree of freedom drag chain presenter. However, a tradeoff exists with the addition of a second degree of freedom as the extra movement might benefit reach, but potentially require significantly greater complexity. Because of this, the addition of a second degree of freedom is considered a 'hopeful' feature for future development. Because of complexity/timing issues faced during subsequent engineering development, this feature has been one of the first compromises.

Commentary on Selected Concept: Fixation and Influence

When undergoing concept generation and downselection, it can be useful to consider how design fixation and external influence might have impacted the final selection by obscuring true process objectivity [73]. Because of the fairly broad and complex scope of this problem space, no complete solution was immediately clear and obvious at the start. Instead, a fairly rigorous and deliberate process was employed to arrive at solutions that properly address the various critical aspects of the user experience (Sequential Combination of Sub-Functions, p. 18). In this sense, little fixation on a particular solution strategy has been present. Admittedly though, the concept tree pruning enacted throughout the ideation process represents a potential avenue for fixation concerns to arise. Priority was placed upon selecting concepts that were feasible, as determined by the prevalence of benchmarks and component maturity. This led to the dismissal of more novel and undeveloped ideas. For instance, we decided to narrow our focus to belt-style restraints rather than explore untraditional ideas such as inflatables or electromagnets, which arguably reflects a fixation on existing solutions. However, there was notable motivation to do this beyond pure ubiquity; solutions within this design space are informed by a long history of rigorous testing and standards [48], [49], and components are widely available. Thus, the central motivation of these pruning decisions was not to simply emulate existing solutions, but rather to determine solution strategies that could be appropriately tackled in this project's short operating timeline. The drag chain presenter, for instance, has little precedent in such a context but is nonetheless the chosen concept strategy for further development.

With regards to influence, the project sponsor (GM) has certainly held significant sway over how the project focus has developed. For example, the scope of this work was initially very broad, but has been narrowed largely through sponsor involvement and input. Our aim has been shifted away from the buckling or grabbing sub-functions to the reach space because current GM teams are more focused on the former (leaving more room for us to investigate the latter) [72]. Our sponsor has also been vocal about their desire to pursue drag chain presenters (an idea they proposed) for their novelty as well as their potential gains in packaging size and retrofitting adaptability. Despite this strong influence, deliberate effort was made to remain objective throughout the selection process. To avoid personal subjectivity and/or distortion of the concept candidate ratings, evaluation of the Pugh matrix (Table 8, p. 23) was completed individually by each team member before being discussed and combined for final ranking. Because of this, we feel confident that the selected concept represents an objectively-motivated embodiment of the fundamental requirements and specifications considered in this work, rather than a misguided and subjective reflection of sponsor influence.

PROPOSED CONCEPT DESIGN: ALPHA PROTOTYPE

Concept Overview

As motivated through systematic concept generation and downselection, the chosen solution strategy to safely and accessibly restrain wheelchair occupants in an AV setting is a single stage belt system with grab handles, funnel buckles, and a drag chain presenter. This concept design has been chosen to reflect the needs of wheelchair users with potential impairments in vision, dexterity, and/or upper body mobility, while simultaneously addressing the functional sequence of user actions (*reach/grab/route/buckle*). Figure 13 (p. 26) presents an overview of the selected concept, demonstrating how the various subsystems interact to form a complete solution.

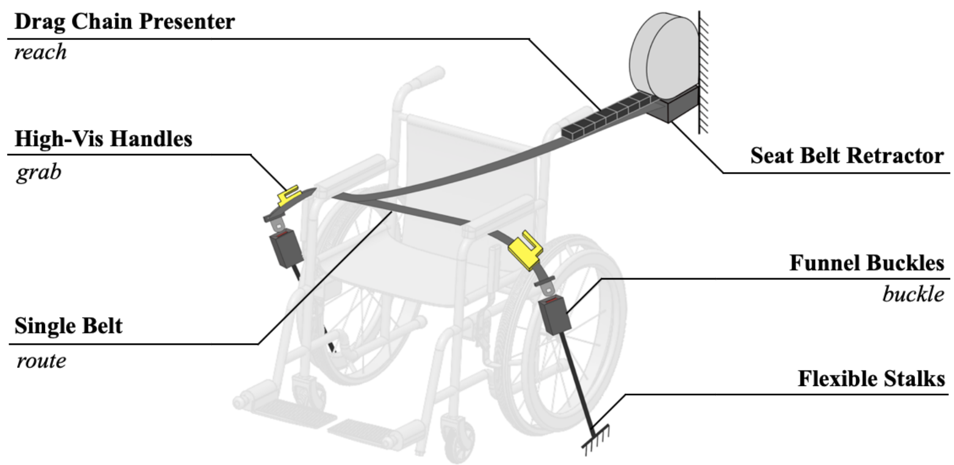


Figure 13: Overview of selected concept: single belt with grab handles and funnel buckles with drag chain presenter. Note that the primary user functions (*reach/grab/route/buckle*) are labeled in the figure to contextualize the relevant subsystems. Image modified from [74].

As illustrated in Figure 13, the proposed concept design involves two separate buckling locations in order to enable proper belt routing — and thus appropriate belt fit — for wheelchairs with closed armrests. The funnel-guided buckles are mounted on flexible stalks to better accommodate different wheelchair sizes, a common practice in retrofitted vehicle design [75]. Though discussed later in more detail, the drag chain presenter is located at the upper anchor point and is ancillary to the structural operation of the traditional retractor mechanism.

To understand how the complete system functions, it is useful to consider a prospective sequence of operation, depicted in Figure 14. First, the wheelchair user positions their chair between the two buckle stalks (likely assisted by a wheelchair docking system). At this point, the drag chain presenter is fully retracted and both seat belt latch plates/grab handles are located at the upper anchor point. Next, the drag chain presenter extends towards the user (via a momentary switch) to aid with reaching the belt, while the handles assist the user with grabbing. The user then sequentially buckles at location 1 and then location 2 (as illustrated in Figure 14), making sure to appropriately route the belt through the wheelchair armrests. With the user fully secured, the drag chain presenter retracts back to the seat belt retractor and the process is complete.

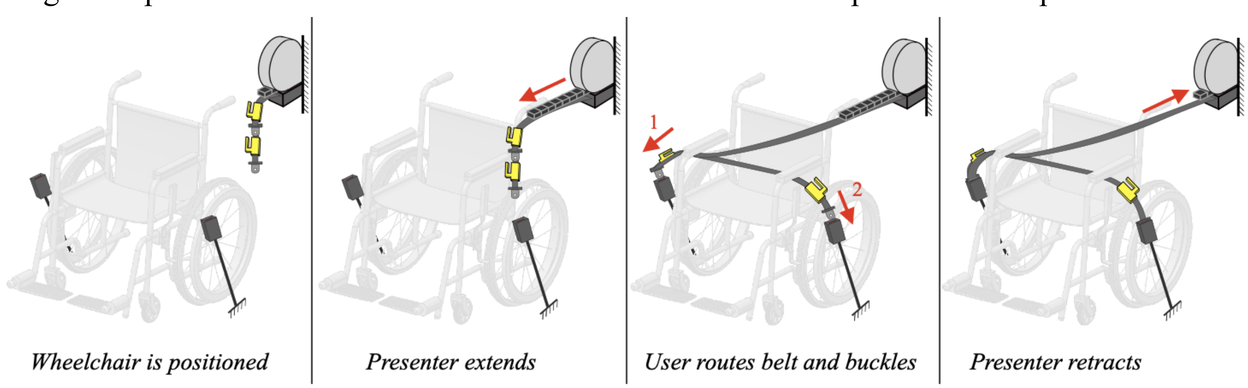


Figure 14: High-level sequence of design operation, from initial wheelchair docking to final securement.

Handle and Buckle Design

As discussed during product benchmarking (p. 4) and concept generation (p. 15), relatively developed solutions exist to address grabbing, manipulating, and securing a buckle restraint for users with impaired dexterity. Consequently, the handle and buckle subconcepts considered in this work will largely be demonstrative; little engineering rigor nor user testing will be performed to generate thoroughly-developed solutions. Nonetheless, high-level concepts for both the handle and buckle are presently discussed, though not used in the final prototype.

Figure 15 depicts a conceptual model of the belt handle device intended to aid with grabbing and manipulating the restraint. As pictured, the device is colored to be visually contrasting with the environment and thus assist users with impaired vision (refer to the 'easy to see' sub-requirement, Table 4, p. 13). The design is low-profile and ergonomic to promote user comfort, while having an open-ended handle that enables those with limited finger dexterity to manipulate the system with their palm. This concept model is largely based on a similar device created by the accessibility-focused social media account *TechOwlPA* [76]. Because of the complex geometry and representative nature of this component, 3D printing will likely be used for the prototype model.

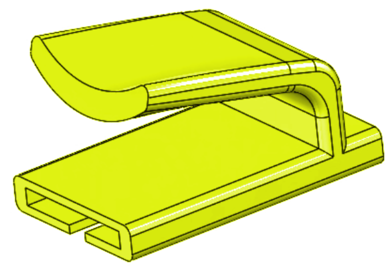


Figure 15: Conceptual model for high-visibility seat belt grab handle.

Figure 16 illustrates the intended design for the funnel-guided buckle receptacle. Linear guide ramps are placed orthogonally in the plane of securement to assist with aligning and securing the buckle latch plate. Additionally, a large release button is located on the side of the buckle; an attractive feature for users with limited hand dexterity as determined through relevant user interviews [27]. Similarly to the handle component, 3D printing could be used to construct a ramp assembly that can be added to a preexisting buckle receptacle.

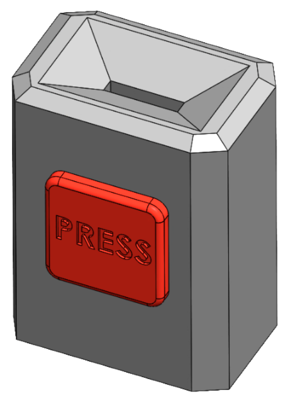


Figure 16: Model of funnel-guided buckle.

Drag Chain Presenter

In the scope of this work, the drag chain presenter is simultaneously the most complex and least understood subsystem, and will therefore represent the central focus of subsequent engineering design and analysis. Though drag chains are frequently used in industrial settings for passive cable routing [77], employing them for actuation is far less common. However — as discussed in Concept Selection (p. 23) — drag chains present a unique opportunity to create a seat belt presenter with a long stroke length and a small package size. Figure 17 (p. 28) presents a functional sketch of the intended design, with callouts for the major components. Note that engineering analysis will be leveraged later in this work to refine dimensions and generate a detailed design solution (refer to Final Design, p. 42). The present goal is simply to communicate the proposed mechanism at a high-level.

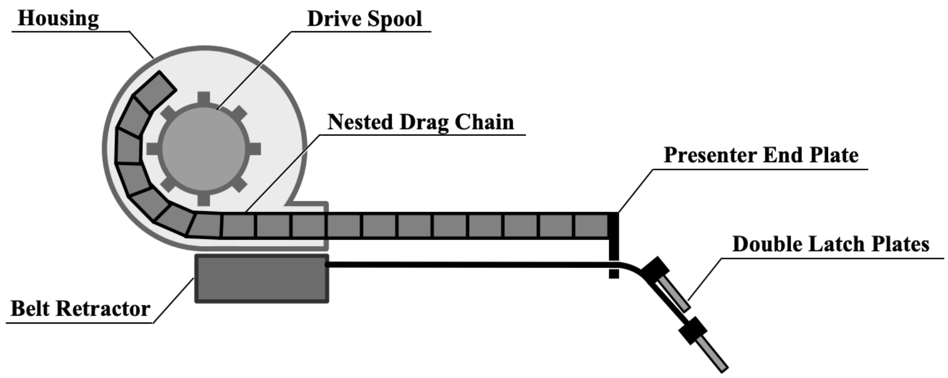


Figure 17: Cross-section schematic overview of drag chain presenter assembly, with callouts for major components. Note that this sketch shows the presenter at partial extension.

The central action of the presenter is the linear extension of the drag chain via rotation of the drive gear. Because the seat belt assembly is routed through the end plate located at the tip of the drag chain, the belt is ‘presented’ from the retractor as the drag chain extends. As such, this mechanism is intended to be ancillary to existing seat belt assemblies, employing off-the-shelf seat belt components and hardware such as retractors and belt webbing. A key aspect of this design is that — when the presenter is fully retracted — the end plate sits flush against the seat belt retractor. This decouples the structural demand of the presenter and retractor assemblies, removing the presenter from the force path and instead leveraging the crash test worthiness of traditional seat belt hardware to satisfy the strict FMVSS 209 and RESNA WC-4 safety standards (discussed in Relevant Standards, p. 11). Figure 18 now presents a high-level schematic of the proposed drag chain design considered in this work.

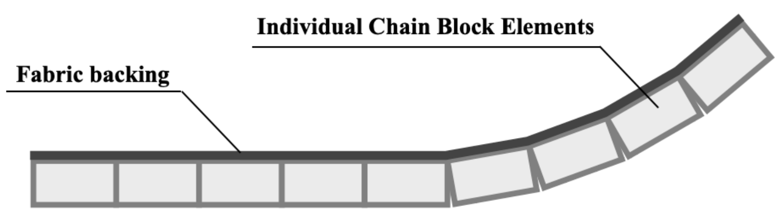


Figure 18: High-level schematic of the proposed drag chain design.

As illustrated in Figure 18, we propose a simplified drag chain construction that consists of individual chain block elements that are secured together using a continuous fabric backing. As opposed to traditional drag chain architectures which employ injection molded links with complex joint geometries [77], this design is believed to simplify manufacturing while potentially achieving greater load bearing capacity. The details of how this design is realized are discussed in later sections (refer to Engineering Analysis, p. 29).

To drive the presenter mechanism, we intend to utilize an off-the shelf DC motor with current limiting end stops or limit switches. This will ensure that the drag chain does not over extend and fall off of the drive spool, or retract so that it breaks the mechanism. Such a design is common in automotive applications (typically used to actuate power windows [78]), and will greatly streamline solution development by employing preexisting hardware. The drive motor will be operated via a momentary switch to allow the user to control presenter extension length. In the Cruise vehicle, this button will be located on a preexisting user-accessible control panel [79]. To better elucidate how the overall drag chain mechanism works in this intended setting, Figure 19 presents a sequential overview of the major steps of operation.

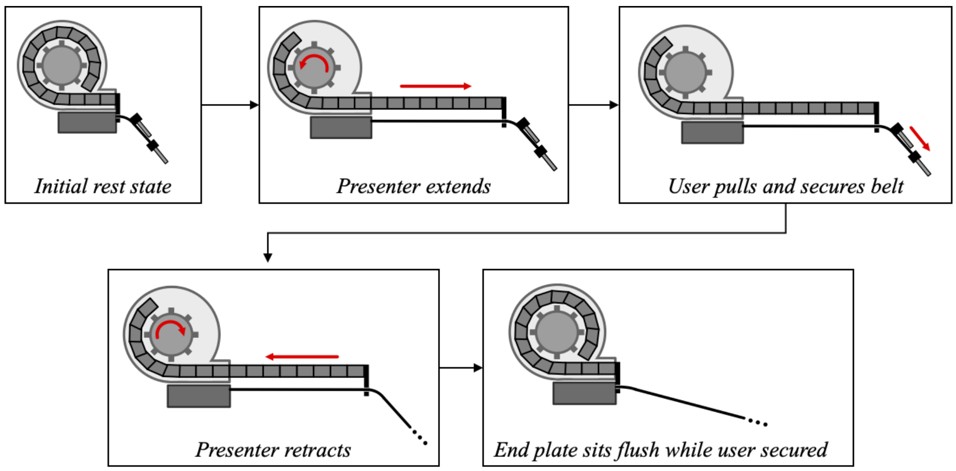


Figure 19: Sequence of operation for drag chain presenter mechanism from initial rest state through final retraction.

As illustrated in Figure 19, the initial rest state consists of the presenter and seat belt retractor both fully retracted. Then — guided by user input — the drag chain extends to present the belt. Next, the user grabs and secures the belt using the double latch plates to route through closed armrest wheelchairs, and the presenter automatically retracts. In the final rest state during vehicle operation, the end plate sits flush against the retractor to decouple the drag chain from the belt forces. To release the seat belt, the user simply unbuckles (no presenting motion is necessary).

ENGINEERING ANALYSIS

Engineering analysis and iteration are essential to produce a refined product that can appropriately address the necessary requirements and specifications. As previously motivated, the central focus of the analysis considered in this work will be directed at the drag chain presenter (Figure 17, p. 28) — not only because it is the most complex subsystem — but because it is the most novel with respect to existing solutions. In an ideal engineering design process, rigorous analysis and design decisions would be immediately driven by knowledge of the anticipated strength/geometry requirements. However, in the context of this work, significant coupling exists between the chain construction/geometry and anticipated loads, so upfront estimation of necessary strength is intractable without a solid understanding of the chain architecture. Thus, a reverse approach is assumed throughout much of the present analytical work, wherein empirical data is used to later form an understanding of desired strength. Consequently, much of the initial testing is comparative in nature, lacking an ultimate operational load to verify absolute design conformance/strength. Once a promising chain architecture is chosen through the comparative empirical studies, anticipated loads are calculated, and the design conformance/strength is finally verified.

Initial Engineering Analysis

As an initial proof of concept, a high feasibility study was completed to analyze the presenter. Specifically, the drag chain was modeled as a cantilever beam with a hollow rectangular cross-section to roughly estimate the maximum tensile stress experienced at extension. Figure 20 presents this highly simplified geometry and loading condition. To calculate the maximum tensile stress, standard statics equations are employed. First, the second moment of area I is found using Eq. 1 as [78]:

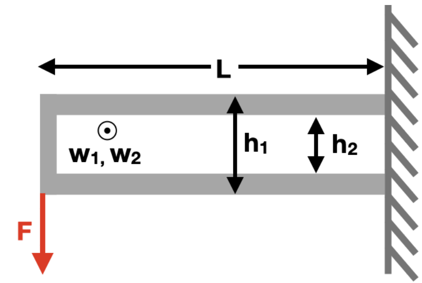


Figure 20: High feasibility study of the presenter as a hollow rectangular beam.

$$I = \frac{w_1 h_1^3 - w_2 h_2^3}{12} \tag{1}$$

where w_1 and w_2 are the external and internal widths, respectively, and h_1 and h_2 are the respective external and internal heights (as shown in Figure 20). Then, the maximum tensile stress σ_{max} is calculated with Eq. 2 as [78]:

$$\sigma_{max} = \frac{FLh_1}{2I} \tag{2}$$

where F is the cantilever load and L is the extended beam length. Prospective dimensions were roughly determined by referencing the standard seat belt width (46 mm [79]), as well as gauging an appropriate extension distance for addressing wheelchair reach. The cantilever load F was referenced to standard retractor tension [48]. Specifically, the following values were used: $w_1 = 60$ mm, $w_2 = 40$ mm, $h_1 = 40$ mm, $h_2 = 20$ mm, $L = 1$ m, and $F = 10$ N. Using Eqs. 1 and 2, this results in a second moment of area $I = 2.93 \times 10^{-7}$ m^4, and a maximum tensile stress σ_{max} = 0.5 MPa. This result is approximately 2 orders of magnitude below the average yield strength of common plastics [80]. Thus — while this analysis is highly simplified — such a result provides confidence that the selected alpha design is reasonably feasible for the anticipated use.

Analytical Sizing of Chain Blocks

To better understand the relationship between material, size, and strength of the individual block segments that comprise the simplified drag chain, a high-level study employing cantilever beam analysis is presently discussed. Though fairly abstracted, the goal of these calculations are to elucidate deeper understanding about how block material and thickness impact strength in order to better inform subsequent design. Thus, this analysis is not meant to be highly accurate in an absolute sense, but rather to uncover scaling behaviors between block geometry and applied load, while providing a comparative focus on materials.

As aforementioned, the drag chain is presently modeled as a cantilever beam, consisting of a fabric backing and individual chain block elements. This theoretical setup is depicted in Figure 21. Two forces are assumed to act on the cantilevered length of chain: a force arising from the user manipulating the belt (F) and the weight of the chain itself (F_g). Specific focus is drawn towards the base of the chain as this is the location of maximum stress following simple moment arm analysis. To model the interaction between adjacent block elements at the base of the chain, the fabric backing is treated as an infinitesimal pivot point, and the counterbalancing force on the face of the block is assumed to be linearly distributed. It therefore follows that the maximum anticipated stress exists at the base of the chain block element. Crucially, our treatment of the fabric backing as an infinitesimal pivot point assumes that the fabric is perfectly inextensible and of negligible thickness. Though a clear oversimplification of the physical reality, such assumptions reflect our present focus on block material and geometry, and greatly aid subsequent calculations.

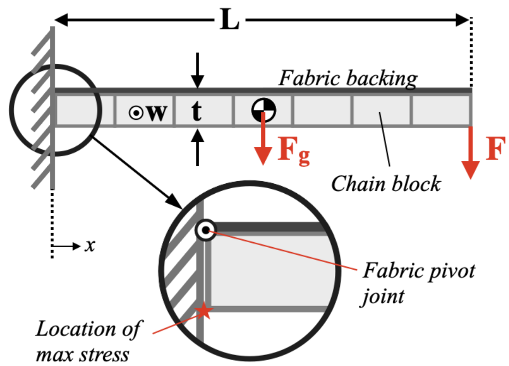


Figure 21: Schematic of cantilever beam analysis used to inform analytical sizing of drag chain block elements.

For the given cantilever model, the maximum stress σ_{max} can be determined using Eq. 3 as [78]:

$$\sigma_{max} = \sigma_{yield} = \frac{Mt}{I} \tag{3}$$

where M is the total moment exerted by the applied forces at the chain base, t is the block thickness, and I is the second moment of area of the chain cross section. Notably, because we are interested in modeling material failure of the chain blocks, this maximum stress (σ_{max}) is set equal to the material yield stress (σ_{yield}). Summing the moments around $x = 0$ (per Figure 21) provides the total moment M in Eq. 4 as:

$$M = FL + \frac{F_g L}{2} \tag{4}$$

where F is the applied force at the end of the chain (from belt manipulation), F_g is the weight of the chain, and L is the total chain length. The force of gravity can be further defined in terms of block geometry and material properties in Eq. 5 as:

$$F_g = Lwt\rho g \tag{5}$$

where w is the width of the chain (into the page as depicted in Figure 21), ρ is the block material density, and g is the gravitational constant. Then, assuming solid chain blocks, the second moment of area I is provided by Eq. 6 as [78]:

$$I = \frac{t^3 w}{2} \tag{6}$$

Making the appropriate substitutions of Eqs. 4-6 into Eq. 3, a fairly complex relationship arises between applied force, material properties, and block geometry, provided in Eq. 7 as:

$$\frac{\sigma_{yield}}{FOS} = \frac{6FL + L^2 wt\rho g}{2t^2 w} \tag{7}$$

where FOS describes the factor of safety used to bolster confidence in solution relevance. Now, with a relationship between applied force (F), material properties (σ_{yield}, ρ), and block thickness (t), the necessary block thickness can be determined based on a range of anticipated loads for different block materials (chosen materials summarized in Table 9). The resulting behavior of block thickness as a function of applied load is provided in Figure 22. Note that the chain width is assumed to be 50 mm in all calculations, reflecting the width of a common seat belt [48], while the chain length is assumed to be 1 meter to attain the geometric specifications provided prior (see Table 4, p. 13). A large factor of safety of 3 is employed as guided by automotive industry standard [81] and sponsor sentiment [82]. HDPE, maple, and aluminum block materials are selected based on uniquity, ease of machining, and sponsor direction [82]. Finally, a broad range of applied forces (10 to 50 N) are considered to best capture the anticipated operational loads, informed by common belt retraction forces [83] and sponsor direction [84]. This operational load is refined later once the chain architecture is defined (refer to Figure 31, p. 39).

Table 9: Summarized properties of chosen block materials [85]–[87].

Material	Comp. yield strength (σ_{yield}) [MPa]	Density ρ [kg/m³]
HDPE Plastic	24.4	958
Sugar Maple	65.0	1050
6061 T6 Aluminum	241	2700

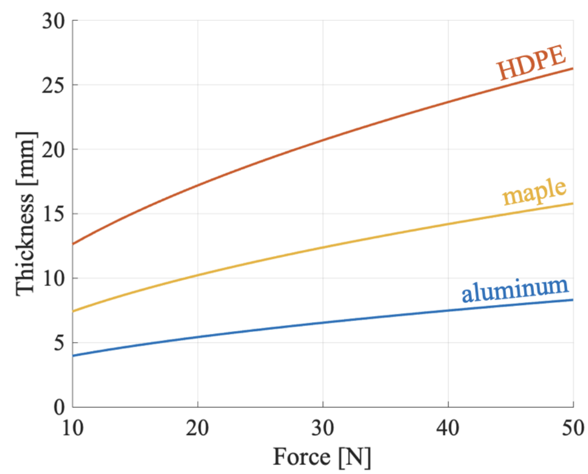


Figure 22: Results of analytical chain block sizing for aluminum, maple, and HDPE for forces of 10-50 N.

As depicted in Figure 22, a nonlinear relationship emerges between the chain's strength (embodied in the amount of force it can withstand) and the individual block thickness. This is ultimately a consequence of the competition between the second moment of area and the weight of the chain in determining the maximum applied stress. Notably, we see a square-root type behavior of block thickness as a function of applied load, suggesting that progressively large gains are made for consecutive increases in thickness. Though significant assumptions were made in creating this model, we may also note a relative range for anticipated block thickness (somewhere around 10 to 25 mm), and compare between material choices. As expected based on the material properties summarized in Table 9, the 6061 T6 aluminum requires comparatively less thickness to sustain the applied load (less than half of the thickness of the HDPE plastic for any given force). This result substantiates aluminum as a viable choice for drag chain architecture. However, a significant number of questions remain about practical geometry, material availability, and securement of the fabric backing, all of which are addressed in the subsequent sections involving empirical testing.

Fabric Backing Glue Studies

With a general idea about chain block material and geometry having been established, we presently discuss investigative empirical work surrounding fabric choice and securement. Ultimately, this study compares the performance of various adhesives when securing a chosen belt fabric to a variety of plastic base materials.

Initial conceptual work favored the use of adhesives to secure the fabric backing to the chain blocks; if a solid interface could be established across the entire face of each individual chain block and the fabric backing, then each block is theoretically constrained to rotate solely about the pivot joint between adjacent blocks. Thus, glue is believed to enable desirable chain kinetics by minimizing the chain's out-of-plane movement. However, concerns persist surrounding the bonding strength of the adhesive, particularly when considering plastic chain blocks (materials such as HDPE are notoriously difficult to adhere to [88]). The choice of adhesive is also highly dependent on the choice of fabric backing material.

Exploratory sourcing of various fabric backing materials suggested that traditional seat belt webbing is a strong candidate to constitute the fabric backing. Initially, canvas-style fabrics were investigated because we believed their natural fiber structure and high porosity would enable strong glue interfaces, but initial strength tests (refer to Figure 25, p. 35) showed unacceptable results (prototype chain with canvas backing failed at an equivalent end load of 8.8 N). Thus, the need for a high tensile strength fabric became clear. In the context of this work, seat belt webbing emerges as an obvious candidate for its tested strength and availability, yet its traditional polyethylene construction and tight-knit weave raises concerns about adhesive effectiveness. Thus, a glue study is performed to inform selection of an adhesive and assess ultimate feasibility.

To assess the performance of various adhesives, a simple force test was performed wherein the adhesive interface between the fabric backing and the chain block was subjected to a pure shear stress. This experimental setup is depicted in Figure 23. Notably, the pure shear loading configuration is believed to best reflect the operational stress experienced by the adhesive interface in the eventual drag chain design. The applied force was measured using a handheld force gauge. As aforementioned, seat belt webbing constituted the fabric backing material. Three different plastic-style base materials (acrylic, polycarbonate, and HDPE) were used as the base block material because plastics were believed to represent the most challenging material to establish a strong adhesive bond (and chain block material selection remained undetermined). Three different adhesives were tested: JB Plastic Weld, E6000, and Gorilla Glue.

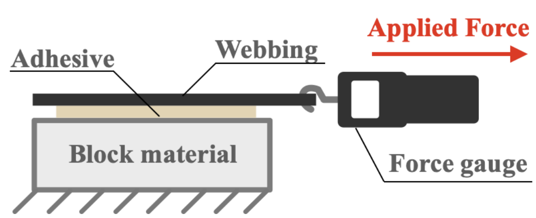


Figure 23: Experimental adhesive shear setup.

JB Plastic Weld and E6000 were selected for their specific focus on plastic-to-plastic bonding, while Gorilla Glue was considered for its expansionary properties which were believed to potentially aid penetration and bonding with the webbing. Each adhesive was used to adhere a test segment of webbing to each base plastic material (for a total of 9 configurations), and clamped for full cure time (24 hours [89]). Failure of the adhesive interface during this shear testing was clear and abrupt; the entire webbing would catastrophically detach from the base material. The ultimate force at failure for each of the 9 configurations are presented in Figure 24.

Notably, the Gorilla Glue performed well for all three plastic base materials (supporting a shear load ≥ 500 N). The JB Plastic Weld resulted in the strongest overall interface when paired with polycarbonate (failing at 601 N), while the performance of the E6000 lagged. Of the various plastic-style base materials tested, HDPE possesses desirable properties in the context of chain block material selection because of its ductility and low cost [90]; acrylic and polycarbonate are known to be brittle [91] and relatively expensive [92]. Thus, Gorilla Glue emerges as a clear adhesive candidate for the eventual drag chain construction because of its comparatively strong performance when bonding seat belt webbing to an HDPE base.

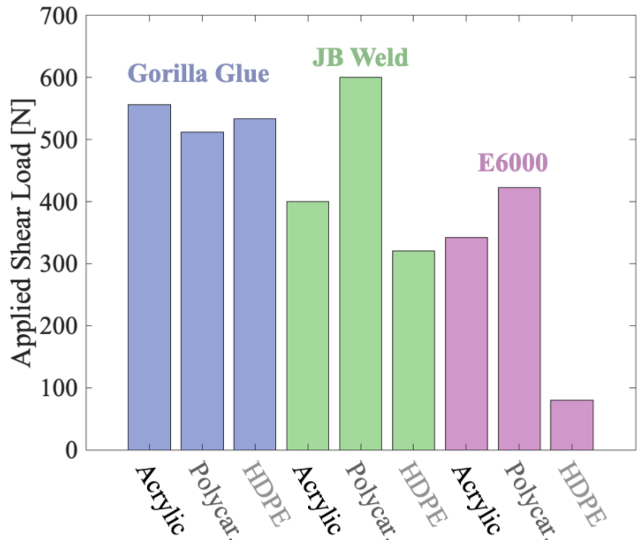


Figure 24: Shear test glue study results show comparatively strong performance of Gorilla Glue.

Despite the promising results of the glue study, some unanticipated concerns arose throughout the course of testing. First, proper bonding of the adhesive required fairly significant clamping pressure (some manufacturers recommend a minimum of 25 psi [93]). Though this was tractable on small test elements, proper curing and bonding of the full scale drag chain could prove difficult given the number of individual chain blocks. Second, penetration of the adhesives into the seat belt material resulted in undesirable rigidization of the webbing. While this absorption and hardening was helpful in creating a strong interfacial bond with the plastic base materials, rigidization of the fabric backing poses a significant concern in the context of the drag chain architecture; the fabric joints between adjacent blocks must be highly flexible to enable the desired kinetic behavior and overall packagability. Thus, the need to consider alternative methods for securing the fabric backing to the chain blocks was established. This concern is addressed in the following discussion surrounding empirical testing of prototype drag chains.

Empirical Testing of Scale Drag Chains

Because of the relative novelty and kinematic complexity of the drag chain concept, thorough analytical analysis is believed to be intractable with the given time and knowledge constraints.

Though some meaningful analytical work has been accomplished with regards to chain block material selection and geometry (refer to Analytical Sizing of Chain Blocks, p. 30), significant assumptions were made regarding force profiles and the behavior of the fabric backing. In order to obtain a more accurate theoretical understanding of chain strength and behavior, significant effort would need to be placed on modeling the plastic deformation of the fabric backing, the potential stress concentrations introduced from the use of fasteners, the changing axis of rotation as the chain defects, and the deformation of block material between adjacent chain elements at highly localized points of contact. However, the relative construction simplicity of the chain design lends itself well to physical prototyping and testing. Thus, to better understand the effect of material selection, block geometry, and fabric securement on overall drag chain strength and behavior, an empirical study on scale drag chain architectures is presently discussed.

As previously motivated, we are interested in comparing the performance and behavior of different block materials, geometries, and fabric securement methods. Specifically, we wish to understand how block thickness impacts ultimate chain strength, uncover the relative performance of aluminum/maple/HDPE as block materials, and explore the use of fasteners and glue to secure the fabric backing. To accomplish this, small-scale drag chains were constructed in the various configurations of interest. These scale chains were then subjected to both a vertical and horizontal load force test, wherein failure was witnessed and defined as permanent stretching of the fabric backing. A high level overview of these two setups is provided in Figure 25 below.

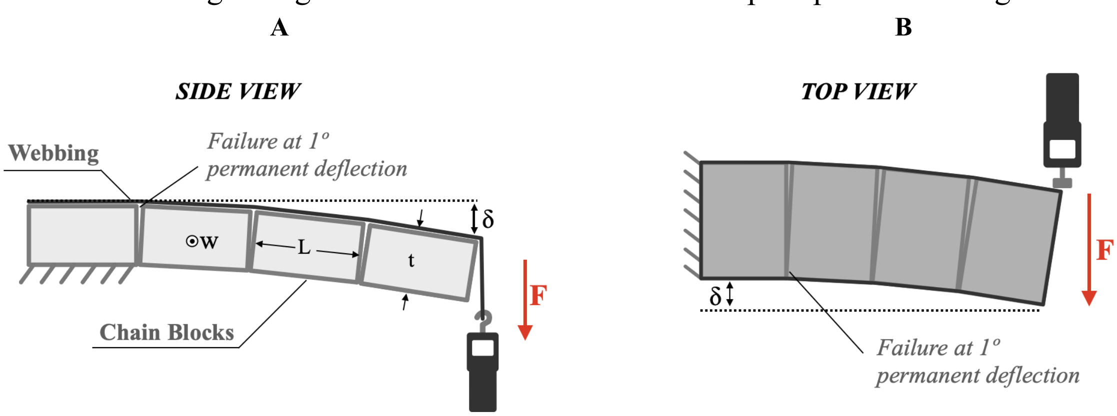


Figure 25: Vertical (**25A**) and horizontal (**25B**) empirical load testing of scale drag chain elements. Deflection (δ) was measured as a function of applied force (F), with failure determined at 1° of permanent deformation at the interface between the base block and the adjacent block.

As depicted in Figure 25, each scale drag chain consisted of four block elements. To conduct each test, the scale chains were positioned in a cantilever configuration by clamping the base block to a rigid table. A known force was then applied in both the vertical and horizontal direction using a handheld force gauge. Deflection (δ) was measured as a function of applied force, using digital calipers. Failure was defined as 1° of permanent deflection between the clamped base block and the next adjacent block (shown in Figure 25A), as measured using a digital level. Notably, because the base block was clamped to a rigid base, only three individual block elements and joints were truly cantilevered.

Six different scale chain segments were produced using 6061 T6 aluminum, sugar maple, and HDPE, both with glue and fasteners to secure the fabric backing. Dimensional parity was maintained between the block elements of different materials in terms of width (w, 50.8 mm) and length (L, 38.1 mm), but thickness (t) was varied (refer to Figure 25A for a visual definition of such dimensions). These width and length dimensions reflect the anticipated geometry of the eventual final design, as informed the standard width of seat belt webbing as well as packagability goals. 2” x 1” (50.8 x 25.4 mm) 6061 T6 aluminum rectangular tubing with 1/8” (3.175 mm) wall thickness was used to create the aluminum chain blocks. This hollow configuration was chosen to minimize weight and cost, while being easy to source. The sugar maple and HDPE blocks were constructed out of 16.0 mm and 15.2 mm thick stock, respectively, based on material at hand. Seat belt webbing was used as the fabric backing for all chain configurations, motivated by the aforementioned consideration of its relatively high tensile strength and availability. For the chains involving adhesive to secure the webbing, Gorilla Glue was used following the results of the previously discussed glue study (refer to Figure 24, p. 34). For the chains involving fasteners to secure the webbing, 1/8” (3.175 mm) aluminum rivets were used for the aluminum blocks, while #6 (3.505 mm) wood screws were employed for both the maple and HDPE. Washers were used in both scenarios to distribute the clamping load across the fabric backing. Images of the three scale chains involving fasteners are provided in Figure 26 below for reference. Note that these images were taken after destructive testing (hence the particularly large gap in the maple chain).

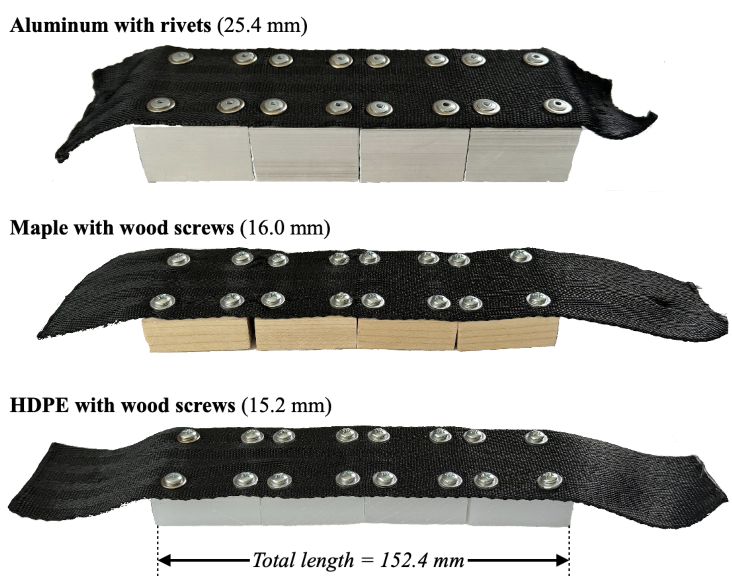


Figure 26: Scale prototype chains of aluminum, maple, and HDPE construction with associated thicknesses in parenthesis. Note that all chains are of equivalent length (152.4 mm) and width (50.8 mm).

Figure 27 presents the results of the vertical load test for the six different scale chains, as well as a more traditional off-the-shelf plastic drag chain to provide a point of reference/comparison [94]. Notably, this reference drag chain had links of equivalent width (50.8 mm) and length (38.1

mm) to the prototype chains we fabricated. As is immediately evident, the chains employing fasteners vastly outperformed those using Gorilla Glue, as well as the off-the-shelf drag chain. Furthermore, the aluminum blocks with fasteners outperformed those of maple and HDPE construction with wood screws. However, as aforementioned and indicated within the figure, these blocks are of varying thickness so direct comparison across materials/fastening type is not appropriate. The effect of block thickness must be separated from the strength performance.

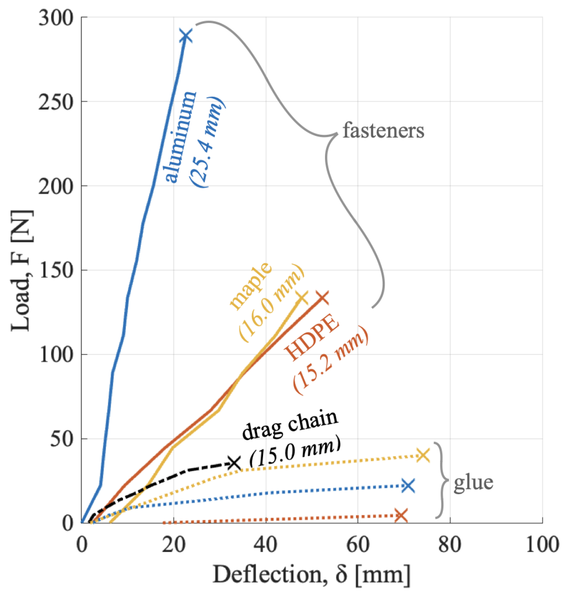


Figure 27: Results of chain vertical load testing.

To better understand the relative performance of the different block materials and fastener types, the effect of thickness on ultimate chain strength is presently analyzed using simple moment arm calculations. Recognizing that stress will be concentrated at the base of the cantilevered segment, we can define a critical force (F_{critical}) located in the webbing at the base block. This agrees with our empirical witnessing of failure; permanent deformation tends to occur at the fabric joint between the clamped base block and the first adjacent cantilevered block. Then, recognizing that the base of the blocks serves as the pivot location, the moments around this point can be used to define the critical force (F_{critical}) as a function of geometry and applied load in Eq. 8 as:

$$F_{critical} = \frac{FL}{t} \tag{8}$$

where F is the applied load, t is the block thickness, and L is the total cantilevered chain length. Figure 28 helps to visualize this analysis, with callouts for the relevant dimensions and forces. Because the critical force is what ultimately influences the deformation of the webbing and therefore the failure of the scale chain prototypes, it is the metric by which comparisons can be made across chain geometries. Because the prototype chains are of equal length (i.e. L is consistent), the empirical applied load results (F) can simply be divided by the respective thickness of each prototype chain (t). This scaling therefore enables meaningful consideration of material choice and fastener type by negating the influence of block thickness. Figure 29 presents the results of this scaling. Notably, only the prototype chains with fasteners (i.e rivets or wood screws) are considered because those using adhesive showed little promise.

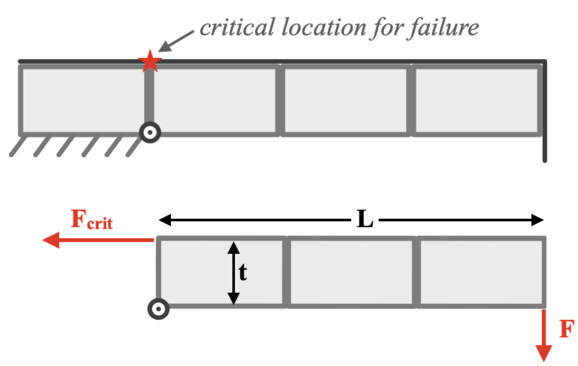


Figure 28: Moment analysis involving critical force.

As can be seen in Figure 29, the aluminum blocks with rivets outperformed those of HDPE and maple construction with screws, even once the effects of thickness are removed. Because the main mode of failure was observed to be the stretching of the seat belt webbing (and little deformation was observed on the individual block elements), performance differences between the chains can be primarily attributed to the type of fasteners. This is substantiated by the nearly identical performance of the HDPE and maple chains, which both employed the same wood screws. More specifically, the aluminum construction with rivets achieved a 30% greater maximum scaled load, and a 53% reduction in deflection at failure. This performance discrepancy can possibly be explained by the smoother surface of the rivets, which avoids cutting the fabric backing or localizing stresses like the wood screws. The rivets also enable a higher clamping force, which might help distribute the load among the webbing. We might also note that the chosen simplified drag chain construction considered in this work (using blocks and a fabric backing) outperformed a more traditional off-the-shelf drag chain design when scaled for thickness, supporting the effort to further develop this concept.

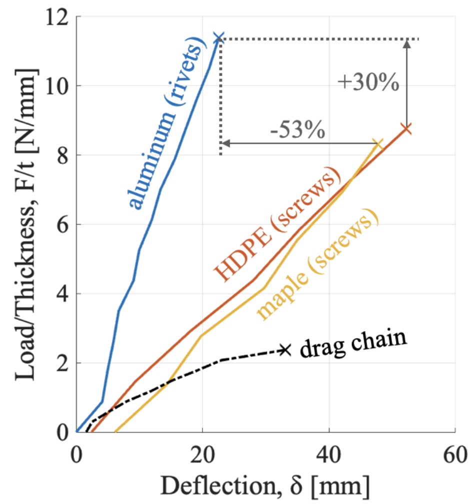


Figure 29: Vertical load test results, scaled by chain block thickness.

Finally, the results of the horizontal load testing are now presented and compared to those of the vertical load test. These results are presented in Figure 30. Notably, for each of the three drag chain designs involving fasteners, the stiffness is significantly greater in the horizontal direction than in the vertical direction. Furthermore, failure is not shown in Figure 30 because noticeable permanent deformation could not be achieved given the maximum force limitation of the handheld force gauge used in testing. Note that the results are not scaled by thickness in Figure 30, as was done for Figure 29. Thus, this result justifies our focus on vertical loading because of the chains' relative weakness in such direction.

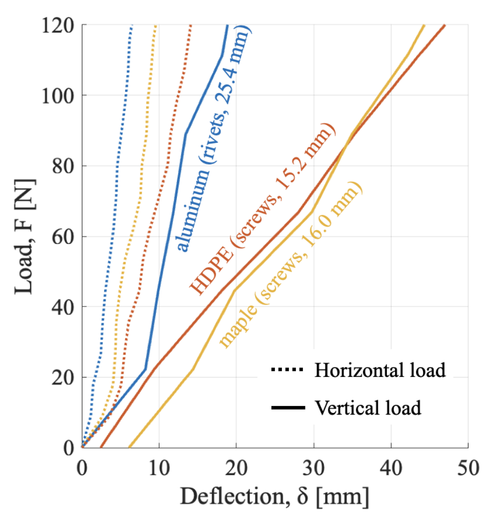


Figure 30: Results of horizontal load test substantiate present focus on vertical loading conditions as main mode of failure.

Our empirical study of drag chain architecture substantiates the aluminum architecture with rivets and seat belt webbing as a comparatively strong and stiff construction. However, the discussion up to this point has been purely comparative; no absolute verification of the chain strength has been made. As aforementioned, determination of the anticipated operational load of the chain is dependent on knowledge of chain material and geometry. Now — equipped with our empirical results and a promising chain architecture — the anticipated operational load can now be estimated. This semi-empirical analysis is discussed next.

Semi-Empirical Estimation of Operational Belt Load

Following the empirical testing of various prototype drag chains, an aluminum architecture with rivets and belt webbing emerged as the strongest and stiffest configuration of those tested, irrespective of block thickness. However, the aluminum stock sourced in this work is significantly thicker than that of the maple or HDPE (25.4 mm versus 16.0 mm and 15.2 mm, respectively). The aluminum chain architecture therefore represents a compromise in package size, in addition to comparatively greater weight and cost. Thus, in order to weigh these advantages and disadvantages, an accurate understanding of the anticipated operational load on the chain must be established. Such an estimation will help determine whether the increased strength and stiffness of the aluminum construction is necessary.

An analytical model — similar to that previously developed for sizing the chain blocks (p. 31) — is now presented to estimate the operational load on the chain when operating in the Cruise vehicle environment. The entire extended length of chain (L = 1 m) is assumed to behave as a cantilever beam. Two primary forces are assumed to act on the cantilevered chain: the force of gravity (F_g) and the force of the belt being manipulated by the user (F_b). The force of the belt (F_b) can be further defined in terms of the tension in the belt retractor (T) and the force of friction of the belt through the presenter opening (F_f) in Eq. 9 as:

$$F_b = T + F_f = T(1 + \mu) \tag{9}$$

where μ is the coefficient of friction between the belt and the presenter opening. Figure 31 depicts a visual representation of this modeling setup.

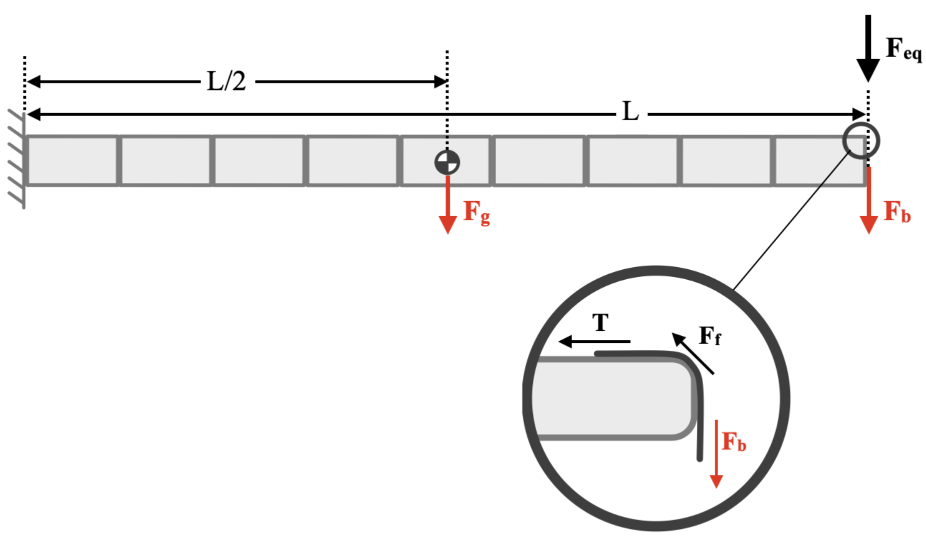


Figure 31: Cantilever beam analysis to determine the operational end load (F_{eq}) of the drag chain as a result of chain weight (F_g) and the force of belt manipulation (F_b).

Ultimately, the goal of this analysis is to find an equivalent end-loading force (F_{eq}) so that a direct comparison can be made against the empirical results discussed prior. This equivalent end-loading force, from the perspective of the stress experienced by the base of the cantilever chain, can be defined by Eq. 10 using moment arm analysis as:

$$F_{eq} = F_b + \frac{F_g}{2} = T(1 + \mu) + \frac{m_{chain} g}{2} \quad (10)$$

where m_{chain} is the total mass of the chain and g is the gravitational constant. Because the majority of these variables reflect aspects of components that have been prototyped or are in possession (such as the belt retractor), they are easily found. The scale aluminum chain consisting of 4 blocks weighs 207 g, so a full 1 meter chain of 27 blocks can be estimated to weigh approximately 1.397 kg. Additionally, the tension of the retractor used in this work is 8 N, as measured by a handheld force gauge. Thus, the only remaining unknown variable is the coefficient of friction, μ. To empirically measure the coefficient of friction, a relatively simple test is conducted wherein a known mass (m) is hung from a segment of belt webbing, and the webbing is routed through a representative D-ring from a seat belt assembly provided by GM. A handheld force gauge is then used to measure the force (F) required to just barely move the belt. This experimental setup is depicted in Figure 32. Notably, the design and plastic construction of the seat belt D-ring is similar to what is anticipated for the final presenter end, substantiating the validity of the resulting coefficient of friction estimate.

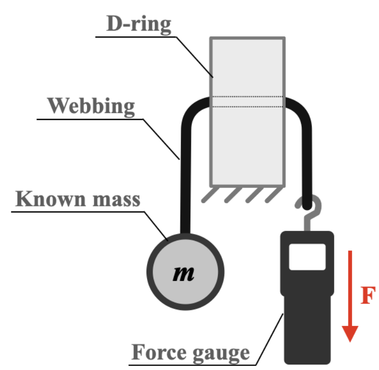


Figure 32: Experimental friction setup.

A simple balance of belt tension for the experimental setup shown in Figure 32 reveals the following relationship between applied force (F) and the known mass (m) in Eq. 11 as:

$$F = mg + \mu(F + mg) \quad (11)$$

Thus, with knowledge of the mass (m) and a measurement of the applied force (F), the coefficient of friction (μ) can be immediately calculated. For a known mass of 500 g, the required force was measured to be 7.5 N, resulting in a coefficient of friction of 0.21. This coefficient of friction is consistent with common estimates for plastic to plastic contact [95]. Thus, with an estimate of the relevant coefficient of friction, the equivalent end-loading force (F_{eq}) can finally be estimated via Eq. 10. Using the aforementioned retractor tension of 8 N and estimated chain mass of 1.397 kg, the anticipated operational end-load of the drag chain is estimated to be **16.5 N**. This is a crucial estimate that will finally enable critical evaluation of the empirical drag chain strength data previously presented. This evaluation follows in the subsequent section. Notably, we have presently considered only the force of gravity experienced by the aluminum drag chain. Because the maple and HDPE are made out of lighter materials, the estimated operational end-load is slightly less (approximately 14.0 N for both as a consequence of nearly equivalent weights). It is worth mentioning that because the force of gravity acts midway through the cantilever chain length, the equivalent force has a comparatively low sensitivity to changes in mass.

Final Chain Architecture Selection

With a robust estimate of the operational end-load of the drag chain, the empirical results of the prototype drag chain tests can finally be evaluated in an absolute sense to determine the best-suited chain architecture. Notably, the empirical results reflect the force sustained by scale segments of chain (4 blocks), while the operational end-load estimate is for a full scale chain (27 blocks). Thus, the empirical force data must be scaled up to the full 1 meter target chain length. Thankfully, this can be easily accomplished by leveraging the linearity between force and length that results from moment arm analysis. Specifically, to maintain parity of the critical force (F_{critical}) experienced by the base of the cantilevered chain per Eq. 8 (p. 37), an increase in length (L) must be countered by an equal and opposite scaling of the end load (F). Thus, to scale the results from 4 blocks up to a length of 27 blocks, the empirical force data must be multiplied by a factor of 4/27. The results of this scaling and the ensuing comparison against the operation end-loads are summarized in Figure 33.

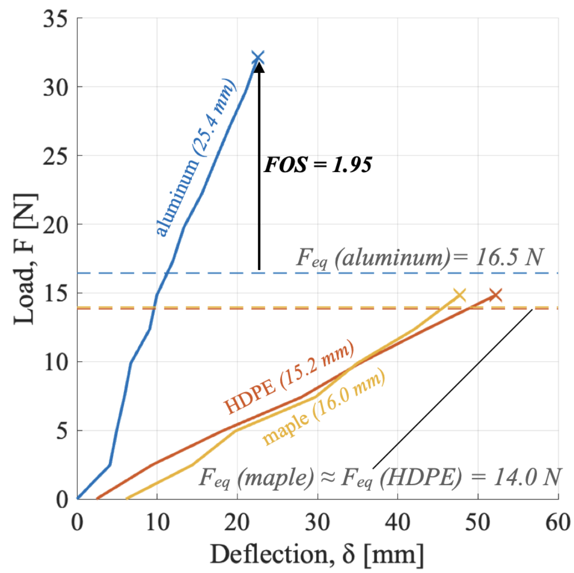


Figure 33: Verification of empirical chain force data.

As depicted in Figure 33, all of the prototype chain architectures surpass their respective estimations for operational end-loading when scaled to the full chain length. However, the maple and HDPE chains are on the precipice of failure, both possessing a factor of safety (FOS) of just 1.06. In contrast, the aluminum chain has a FOS of 1.95. Thus, the aluminum construction with rivets and webbing emerges and the sole viable configuration of those tested within this work. For this reason, the aluminum chain architecture is selected for the final design.

Through the course of this engineering analysis, we have broadly explored the influence of material selection, block geometry, and securement method of the fabric backing in a comparative sense. Then, having established some promising configurations, the anticipated operational end-load has been calculated as a function of chain material properties and belt forces. Finally, these operational load estimates have been compared to the experimental strength of the relevant chain architectures, enabling absolute verification of chain strength. As aforementioned, the prototype chain consisting of aluminum blocks and riveted belt webbing emerges as the most viable option, with a FOS of 1.95. This chain architecture, and the associated infrastructure to create a functional presenter system, are further discussed and defined next in our presentation of the final design.

FINAL DESIGN

The final design of the drag chain presenter mechanism is now discussed in detail, as informed by the results of our engineering analysis. Notably, the scope of our final build design has been narrowed to simply the drag chain presenter due to budgetary and time constraints. Though unfortunate, this decision is substantiated by the novelty and complexity of the drag chain presenter; the other components of the previously discussed concept design (such as the handle and buckle guide) are far more developed in industry and trivial to implement. Thus, the following discussion and work is focused on the presenter mechanism.

Overview of Presenter Assembly

Having determined the appropriate drag chain architecture to support the anticipated operational loads of the presenter mechanism, the full design solution can now be discussed. Figure 34 provides an overview of the final design, with callouts for the major components.

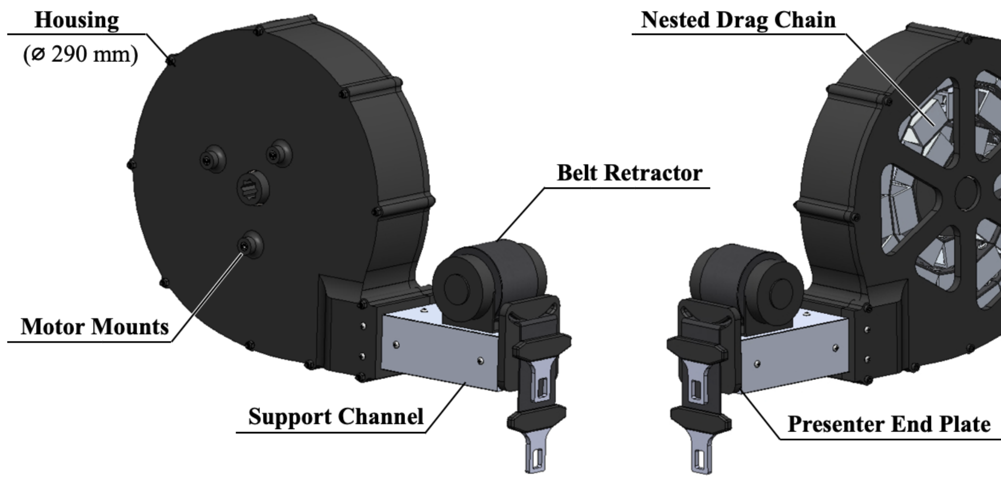


Figure 34: CAD schematic of final presenter design solution, with callouts for major components.

As depicted in Figure 34, the main body of the presenting mechanism consists of a rigid plastic housing. This structure houses the drag chain, and provides a mounting location for the drive motor. This housing is intended to be 3D printed out of ABS, and has thick (8 mm) walls to ensure appropriate strength. Further refinement of this housing in terms of material usage and strength could be achieved through further calculations or finite element analysis, but such analysis proves out of scope given present time and knowledge constraints. The housing consists of two separate halves that are secured together using long (80 mm) M4 through bolts. The housing is rigidly attached to the support channel, which is a segment of rectangular aluminum tubing that bears the bulk of the structural loading experienced by the presenter during operation, and serves as the mounting point for fixture of the whole mechanism. The belt retractor (provided by GM) is mounted atop the support channel, and the belt is routed through the presenter end plate to enable presentation of the latch plates to the user. Notably, two latch plates are included to enable routing of the seat belt through closed-armrest wheelchairs. The presenter end plate has a smooth and curved opening that minimizes the coefficient of friction (refer to p.

40) and prevents the belt from binding. Notably, the retractor location is different from what was previously envisioned in prior discussions about concept selection (p. 28), as the tension in the retractor will tend to pull upwards on the drag chain in the chain's compliant direction during operation. Despite this undesirable aspect, such a configuration is adopted due to constraints within the interior geometry of the Cruise vehicle as well as sponsor sentiment [82]. To counteract the moment arm from the tension acting on the belt, pretensioned elastic cables are strung through the bottom of the drag chain. This elastic pretensioning also has the added benefit of constraining the chain from undesirable spooling or folding if bumped during operation. A closer view of the final drag chain design and presenter end is presented in Figure 35.

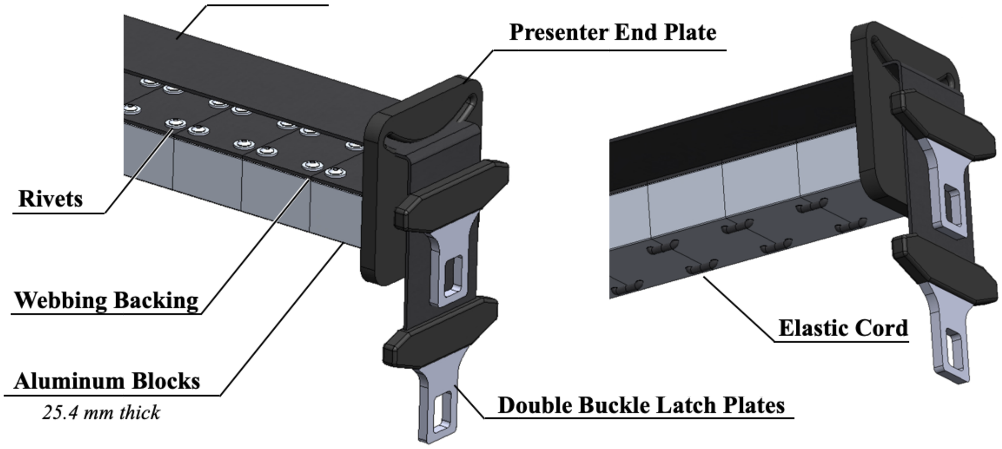


Figure 35: CAD schematic overview of drag chain with presenter end plate.

As previously motivated through the course of this work's engineering analysis, an aluminum architecture employing rivets and a seat belt webbing has been selected due to its favorable strength properties. Specifically, each individual chain block is constructed out of 2" x 1" (50.8 x 25.4 mm) 6061 T6 aluminum rectangular tubing with 1/8" (3.175 mm) wall thickness, and cut to a length of 1.5" (38.1 mm). 1/8" (3.175 mm) aluminum rivets are then used with 9.5 mm O.D. washers to secure the webbing to the individual chain blocks. 1/8" (3.175 mm) elastic cable is routed through openings on the bottom of the blocks to pretension the system. These dimensions and the relevant hole positions are summarized in Figure 36. Note that the holes used for securing the rivets are identical in size and placement to those used for routing the elastic cables, easing subsequent manufacturing (refer to Appendix II).

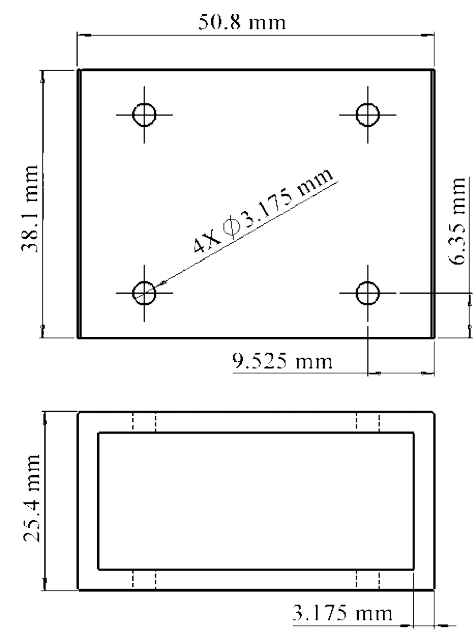


Figure 36: Dimensions of chain blocks.

Figure 37 now provides a view of the support channel, which is intended to help guide the presentation of the drag chain as well as bear the structural loads of operation.

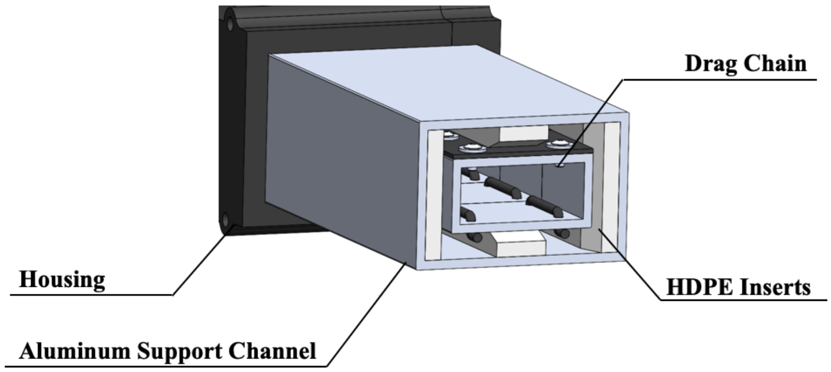


Figure 37: CAD schematic of presenter support channel with HDPE inserts

The support channel is constructed out of 3" x 2" (76.2 x 50.8 mm) 6061 T6 aluminum rectangular tubing with 1/8" (3.175 mm) wall thickness, and cut to a length of 7.5" (190.5 mm). Within the support channel, 8.6 mm thick HDPE inserts are used as guides to minimize friction and help realign the chain during retraction (note the chamfered edges of the inserts). The central role of the support channel is to isolate the 3D printed housing from the significant forces and moments that arise in the chain from operation.

Finally, Figure 38 provides a view of the drive spool about which the chain coils within the presenter housing. Similar to the housing, the drive spool will be 3D printed out of ABS.

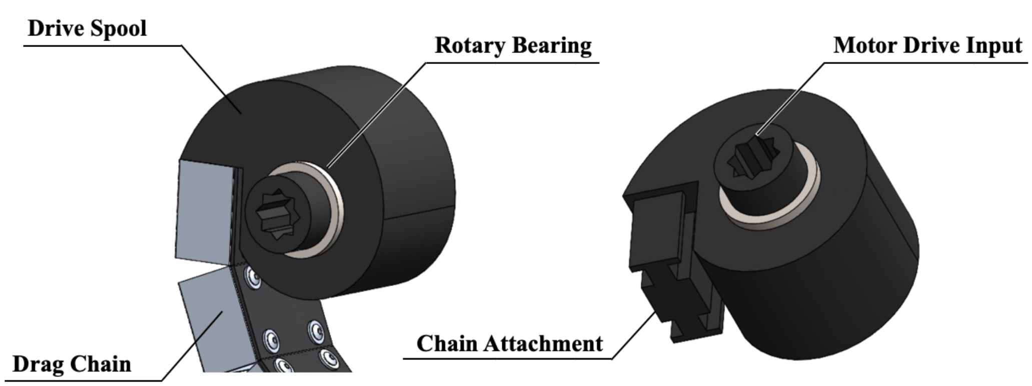


Figure 38: CAD schematic of drive spool used to extend drag chain through motor input.

As shown in Figure 38, the drive spool is internally supported within the presenter housing by two low-profile rotary bearings (37 mm O.D, 30 mm I.D, 4 mm thickness). These bearings will serve to minimize friction and promote a smooth procession of the drag chain during extension and retraction. The shaft of the drive spool has an extruded gear cut that meshes with the selected drive motor (to be discussed later, p. 46). Finally, the spool has a mating feature that resides within the drag chain end block to enable secure and rigid attachment.

Sequential Steps of Operation

To understand how the presenter mechanism functions, it is useful to consider the series of sequential steps during operation. This operation is summarized in Figure 39.

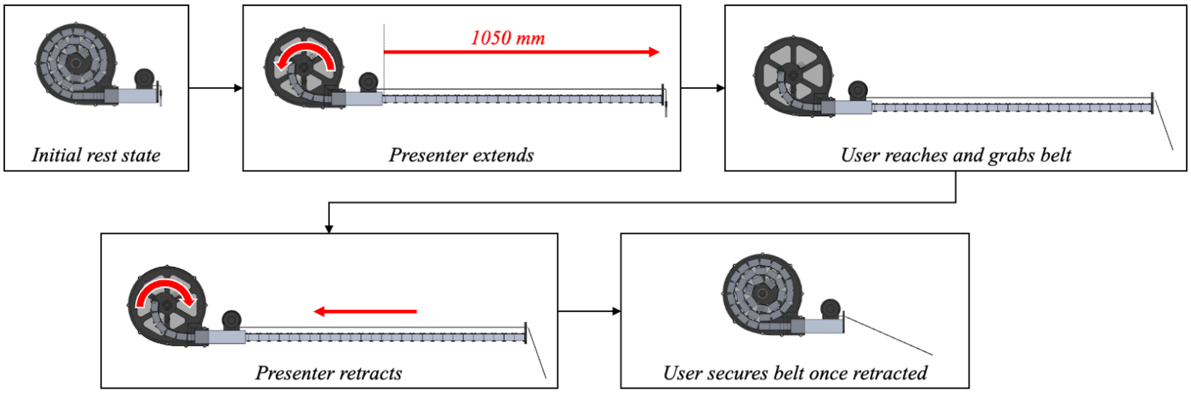


Figure 39: Final design sequence of operations from initial rest state through user buckling and securement.

As elucidated in Figure 39, the presenter begins in the fully retracted state. Then, once prompted by the user via a momentary push button, the presenter extends (with a maximum possible extension distance of 1050 mm). Once the user is able to reach the restraint, the presenter retracts. Notably, the end plate through which the belt is routed sits flush against the seat belt retractor, isolating the presenting mechanism from the force path of the restraint once the user is secured. Finally, the user secures the restraint. This sequence of operations is similar to that previously described in our concept selection (refer to Figure 19, p. 29), though an important distinction can be made based on when the user secures the belt. To better isolate the presenter mechanism from the forces resulting from user belt manipulation, the presenter retracts prior to the user pulling on the belt.

Elastic Pretensioning Calculations

In order to ensure that the tension from the belt retractor does not cause the drag chain to lift upwards and spool, the elastic cables within the chain design (Figure 35, p. 43) must be pretensioned. To determine the appropriate amount of pretensioning to offset the retractor tension, simple moment arm calculations can be performed about the presenter end plate. Specifically, focus can be directed at the final chain block element, as such a location has the least restoring moment from chain weight. The relevant free body diagram to enable such analysis is provided in Figure 40. Equating moments about the fabric pivot yields the necessary tension in the elastic cables (T_{elastic}) in Eq. 12 as:

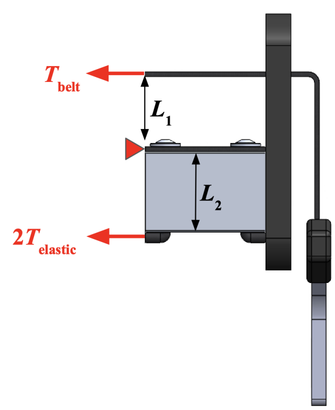


Figure 40: Moment arm analysis for elastic cables

$$T_{elastic} = \frac{T_{belt} L_1}{2L_2} \tag{12}$$

where T_{belt} is the tension from the belt retractor, and L_1, L_2 are the moment arms through which the belt tension and elastic tension act, respectively. Note the factor of 2 resulting from the fact that there are two elastic cables in the final chain design. Recalling the belt tension to be 8 N and using the relevant lengths of 22 mm for L_1 and 27 mm for L_2, the required pretensioning in each elastic cable is approximately 3.3 N. As expected, this force will be easily achievable with the chosen 1/8" (3.175 mm) elastic cables.

Motor Sizing and Verification

With a concrete understanding of the presenter design and the relevant geometries, the necessary torque to extend/retract the drag chain is now estimated to inform motor selection. The torque borne by the motor is anticipated to result from friction within the support channel. Again, moment arm analysis about the extended chain can be used to estimate the resulting frictional forces, and thus find the necessary motor torque. Figure 41 presents the relevant analysis.

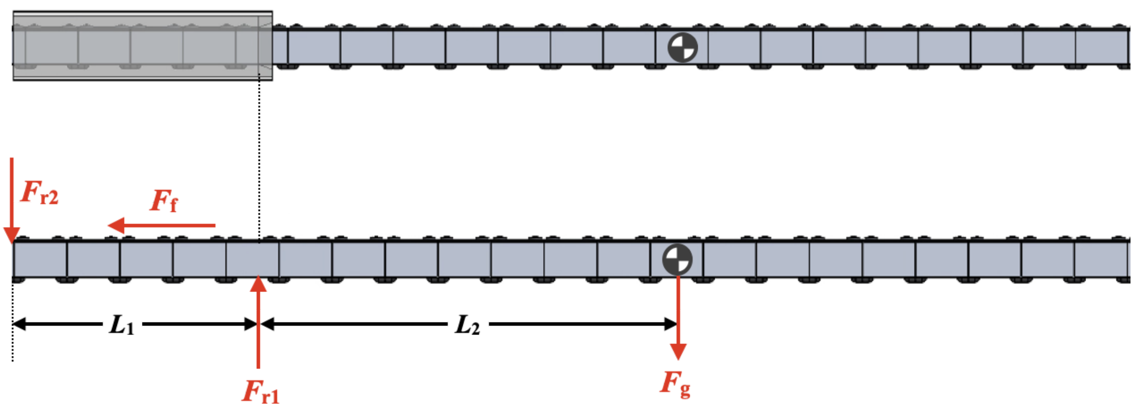


Figure 41: Moment arm analysis to estimate friction within the support channel and required motor torque.

The friction within the support channel will be maximized when the drag chain is fully extended, as the weight of the chain will be at its maximum effective moment arm. Because the sequence of operation has been updated to require the presenter to retract before the user buckles, the weight of the chain (F_g) is the only relevant force. Within the channel, two reaction forces arise to balance the weight of the chain (F_{r1} and F_{r2}). Because some play is expected between the HDPE guides within the support channel and the chain, these forces are treated as point loads rather than distributed (a decision which promotes a conservative result). These point loads will together generate a frictional force (F_f) within the channel, defined by Eq. 13 as:

$$F_f = \mu(F_{r1} + F_{r2}) \tag{13}$$

where μ is the coefficient of friction between the HDPE guides and the aluminum chain. Technically, the top reaction force (F_{r2}) will cause friction between the interface of the fabric backing and the HDPE, but aluminum-to-HDPE contact is assumed instead to ease calculations and promote a conservative result (aluminum has a notoriously high coefficient of friction across many materials [96]). Recognizing that the required torque will be the frictional force (F_f) times the relevant internal housing radius (r), and solving for the reaction forces (F_{r1} and F_{r2}) in terms of the weight of the chain (F_g), the motor torque (T) is expressed in Eq. 14 as:

$$T = rF_f = r\mu(F_{r1} + F_{r2}) = r\mu F_g\left(1 + 2L_2/L_1\right) \tag{14}$$

where L_1 is the internal length of the support channel and L_2 is the length from the channel end to the chain's center of gravity. Using a simple force test experiment similar to that previously described (refer to Figure 32, p. 40), the coefficient of friction (μ) between the HDPE and aluminum was estimated to be 0.15. Then using the inner radius of the housing (r = 135 mm), the chain weight (F_g = 13.7 N), the internal length of the support channel (L_1 = 190 mm), and the distance to the chain's center of gravity (L_2 = 525 mm), the resulting motor torque is estimated to be **1.81 Nm**.

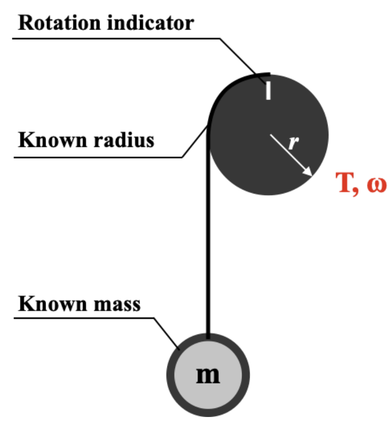


Figure 42: Motor torque test setup.

As previously alluded to, a motor has already been selected for the final design (specifically, the passenger window motor used in a 2007-2015 Mazda CX-9). Though ideal engineering practice would have preferred motor selection after the required torque was estimated, the decision to source the motor early was motivated by time constraints; the electronics and control scheme needed time to be properly implemented. Thus, we presently discuss a brief empirical study on the selected motor to verify compliance with the anticipated torque requirement. The relevant experimental setup is depicted in Figure 42. Essentially, a torque-speed curve was generated by applying torque to the motor and measuring the rotational speed. The torque was applied by hanging a known mass from a pulley attached to the motor with a known radius. The rotational speed of the motor was determined by counting the number of revolutions in a specified time interval using a rotational indicator.

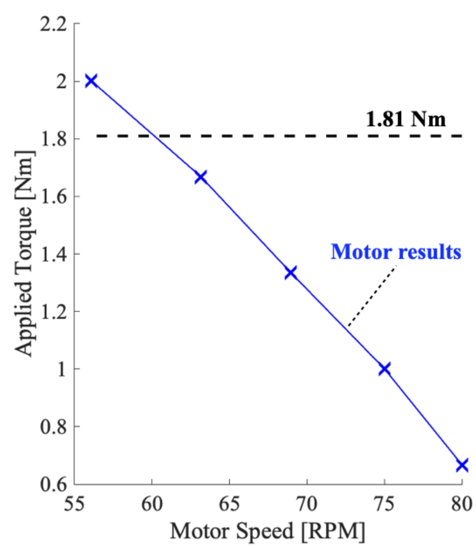


Figure 43: Motor torque verification.

Figure 43 presents the results of the motor testing, along with a comparison to the previously estimated torque requirement. Importantly, the test results demonstrate that the motor can provide the necessary torque. It is also worth recognizing that the motor provides the anticipated 1.81 Nm at fairly high rotational speeds (~60 RPM), suggesting that much higher torque could be provided.

This analysis could be simplified by finding the stall torque of the electric motor and comparing it to the required torque. However, the motor considered in this work has a rather complicated built-in gearbox, so this comparatively complex approach of generating a torque-speed curve was favored to avoid subjecting the motor to unnecessarily high torques that could damage the internal plastic gearing.

Supporting Electronics

To power the motor and enable appropriate control of the presenter for extension and retraction, a fairly simple circuit has been devised and is depicted below in Figure 44.

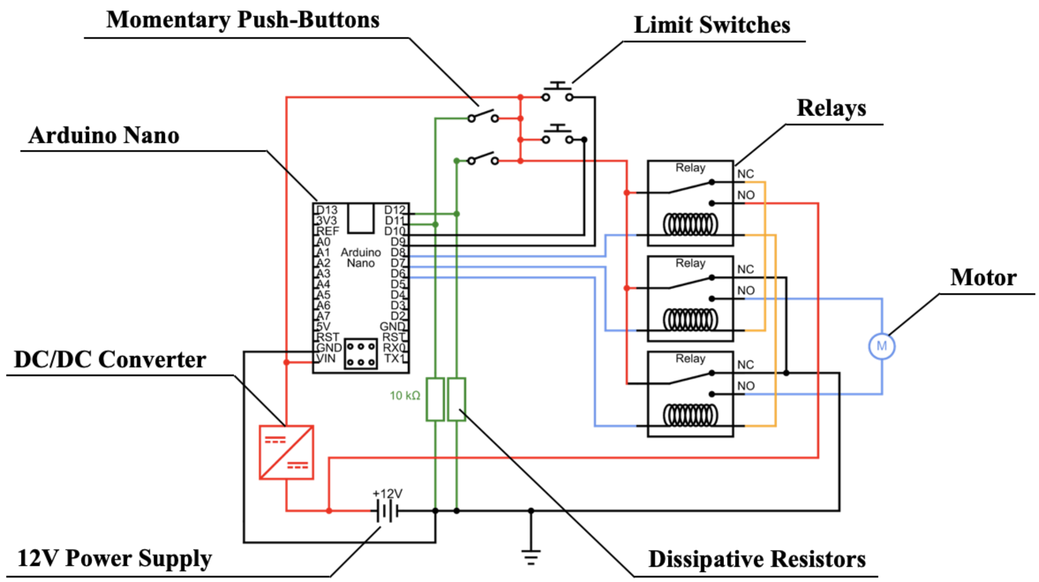


Figure 44: Schematic diagram of circuit used to drive motor and control presenter operation.

As shown in Figure 44, the logical control for the circuit is provided by an Arduino Nano microcontroller. Two momentary push buttons are used to provide user input for extension and retraction, while two limit switches are included to prevent the over-extension/retraction. Notably, in previous discussions about the presenter concept design (p. 28), we discussed the desire to use the motor's built-in current limiting end-stops. However, implementing this proved difficult; the chosen motor requires communication for the vehicle ECU for this functionality to be realized. Thus, simple limit switches located at the end-conditions of the drag chain are used instead. To turn the motor on/off and switch the polarity, three relays are employed in a configuration that simulates an H-bridge. The entire system is powered by a 12V (10A) voltage supply, and a DC/DC converter is used to step down the input voltage to the 5V required by the microcontroller. A 3D printed housing (shown in Figure 45) is used to neatly organize these components while providing an interface for the user to control the presenter action via the momentary buttons. It is worth mentioning that much of this circuit could be streamlined and optimized, but many components were selected based on what team members had on-hand to minimize the need for sourcing and further expenses.

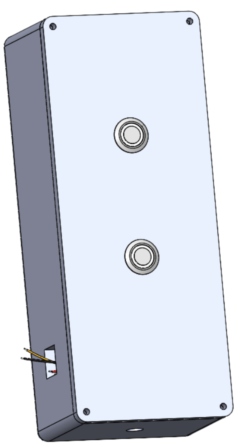


Figure 45: Electronics housing CAD.

Bill of Materials
To accurately assess total prototyping cost of the final presenter design, an in-depth bill of materials has been generated to track costs among all of the different subsystems (refer to Appendix I, Table 15). A majority of components have been sourced off-the-shelf from major retailers such as Home Depot and Amazon. Some components, such as seat belt hardware (i.e. retractor, latch plates, buckle receptacles), have been provided by our sponsor (GM). Finally, some major components such as the housing, spool, and presenter end plate have been 3D printed from ABS filament. The total cost of the prototype system is $297.55.

Manufacturing Plan
Broadly, the final design of the prototype drag chain presenter consists of three main subassemblies: 1) the drag chain, 2) the support channel, and 3) the housing with supporting plastic components. Each of these subsystems have associated tolerances and manufacturing requirements that are discussed separately in Appendix II. Final assembly of the complete presenter system (with exploded model views) is also provided in Appendix II, for reference.

Commentary on Build Design
Through the course of our discussion on the final presenter design, we have detailed the materials, geometries, and processes that have informed the creation of a prototype drag chain presenter. This design has been fabricated, with an image of the prototype build provided in Figure 46. As will be discussed in detail later (refer to Prototype Design Critique, p. 60), the current prototype demonstrates promising attributes when it comes to packagability, stroke length, and general versatility. However, both the drag chain and seat belt currently bind during extension, rendering the system practically unusable. Suggestions to remedy these binding issues are provided later in Recommendations (p. 68).

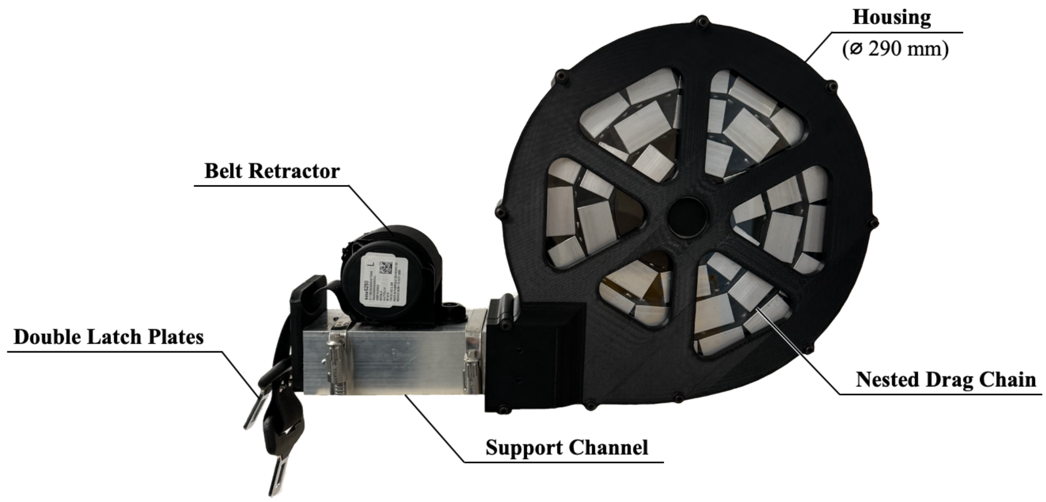


Figure 46: Image of actual prototype build with callouts for relevant components.

Beyond the iteration needed to remedy binding, there is undoubtedly additional room for further optimization and refinement for the commercial setting (such as widespread use in Cruise vehicles). Rather than 3D print major plastic components, assembly difficulty and costs could be reduced at scale through injection molding. Motor sizing could be further optimized, and the control system could be seamlessly integrated into the vehicle interior to be conveniently accessible to the user. In terms of the drag chain design, the entire assembly could be injection molded out of a flexible polymer material, with high tension fibers (such as metal cables). This is discussed in more detail in Suggested Changes for Commercial Implementation (p. 70).

Reflection on Key Design Drivers

The ultimate goal of this project has been to develop a high-fidelity functional prototype with working 2-stage buckling functionality (to demonstrate routing through closed armrest chairs, refer to Figure 13). As discussed thoroughly, the drag chain presenter has represented the central focus of our design work and prototyping efforts; it is simultaneously the most complex and least understood system. Significant engineering analysis and thorough testing have been necessary to develop a refined solution design. Figure 47 presents the key drivers that have guided this development, with explicit consideration of decision order and dependency.

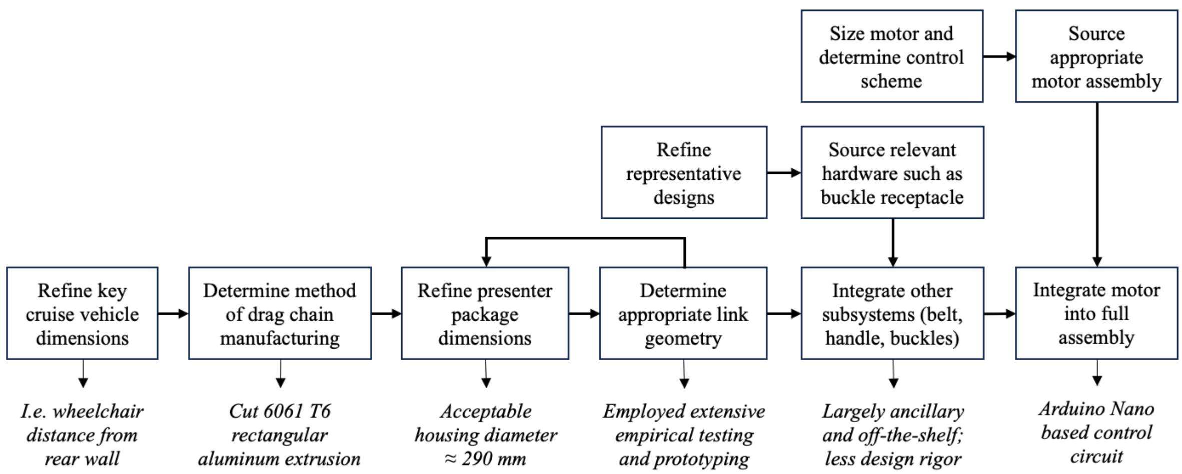


Figure 47: Flow chart of key design drivers that have dictated analysis and evolution of the prototype model.

As pictured in Figure 47, the first concern was refining the relevant interior dimensions of the Cruise vehicle, which had a significant impact on the overall dimensions and layout of the system. Next, the method of manufacturing the drag chain was selected. As previously discussed, individual blocks cut from 6061 T6 aluminum were favored for their ease of manufacturing and tight tolerancing. Then, the presenter package dimensions were broadly defined to inform drag chain sizing as directed by GM and Cruise [82]. The drag chain links were then rigorously analyzed to determine appropriate material, strength, and kinetic behavior. As discussed, this stage involved a significant amount of empirical testing with scale chain models. Notably, the link geometry and package dimensions are closely related, so a feedback loop is shown in Figure 47. Finally, we have assembled the necessary seat belt hardware and implemented the appropriate DC motor/control scheme. Each of these ancillary paths have involved their own development and sourcing requirements, though they have been far less demanding than the central development of the drag chain presenter.

VERIFICATION AND VALIDATION

Verification Test and Results

As will be demonstrated in the subsequent discussion pertaining to design verification, most requirements and specifications have been verified within the scope and timeframe of this project. However, some requirements — such as belt strength, buckle strength, and durability — remain out of scope. As aforementioned, the presenter design leverages pre-existing seat belt hardware and remains out of the force path during operation (refer to Final Design, p. 42). Thus, there is reasonable evidence that failure to verify ultimate strength of the seat belt hardware does not hinder the efficacy of the prototype, nor the legitimacy of the proof of concepts. Below, in Figure 48 is the design of the current test rig, which was used to practically enable verification. As mentioned previously (refer to Commentary on Build Design, p. 49), the prototype system experiences unanticipated issues with drag chain and seat belt binding, severely limiting the usability of the restraint. To still enable verification of requirements that necessitate presenter operation, extension of the drag chain was assisted by hand, and the securement sequence was modified to avoid enacting destructive loads on the drag chain (refer to Figure 39, p. 45).

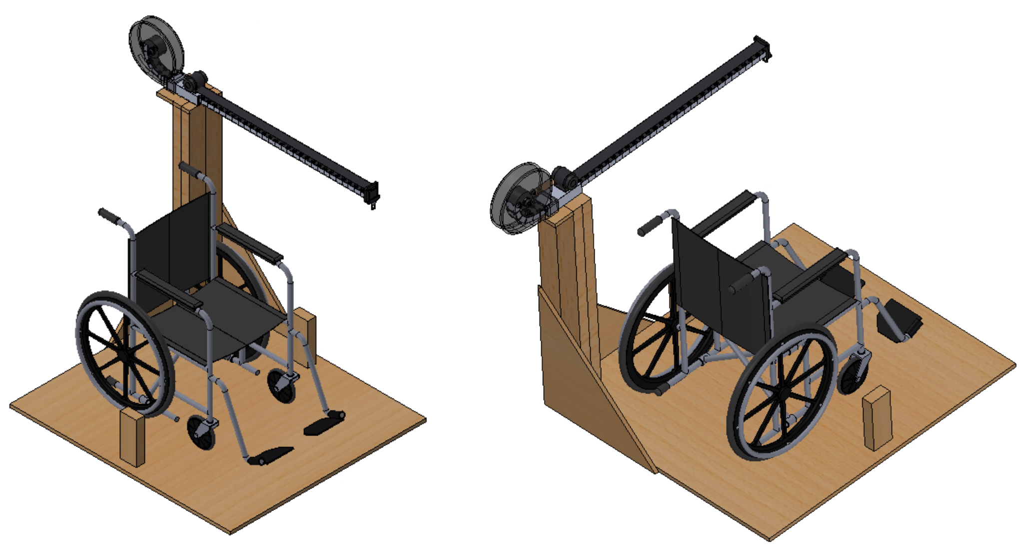


Figure 48: Detailed CAD model of the intended test rig. The setup includes the presenter, a demonstrative wheelchair, and the wood structure to place the components in the correct location.

As depicted in Figure 48, the structural test rig is made out of simple 2x4” lumber and plywood construction, with a reinforced post to mount the presenter mechanism. Notably, two short 2x4” blocks are attached to the plywood base to serve as mounting points for buckle receptacles. Thus, a prototype assembly has been fabricated that illustrates the functionality of the 2-stage buckling architecture (using a demonstrative wheelchair with closed arm rests). The key dimensions of this test rig — particularly as they pertain to the relevant positional specifications — are discussed in detail later (refer to Figure 50, p. 54).

Safety. Verification of the safe requirements shown in Table 11 includes mostly measurement, inspection, and ensuring compliance with the relevant safety standards. As discussed previously, rigorous consideration of the seat belt assembly standards remains out of scope; a decision substantiated by the presenter design avoidance of the belt's force path during vehicle operation.

Table 11: Verification plans to address safety related specifications, with associated justification for testing.

REQUIREMENT	SPECIFICATION	TEST METHOD	RESULTS
Proper belt fitment	· Compatible with 5% female to 95% male range: · Sitting height: **(785 - 965) mm** · Waist: **(599 - 1080) mm** · Chest depth: **(190 - 267) mm** · Compatible belt fit per RESNA WC-4 · Belt width ≥ **46 mm**	*Measurement & Inspection* *Measurement* *Measurement*	· Conformance with **5% female** to **95% male** range dimensionally verified (depicted in Figure 49) · Belt width = **45 mm**
Compliant belt strength	· Compliant with Type 2A architecture tensile loads: · ≥ **22,241 N** for pelvic belt restraint · ≥ **17,793 N** for upper torso belt restraint	*Use of industry standard belts, testing out of scope*	*Use of industry standard belts, testing out of scope*
Compliant buckle strength	· Compliant with loads of: · ≥ **40,043 N** in tension · ≥ **1,779 N** in compression · False latching release force ≤ **22 N**	*Use of industry standard buckles, testing out of scope*	*Use of industry standard belts, testing out of scope*

Proper belt fitment is verified to confirm regulatory compliance with the RESNA WC-4 standard. The relevant test method leverages measurement and virtual inspection, with the results of the modeling picture in Figure 49 for the physiological user range of 5% female to 95% male.

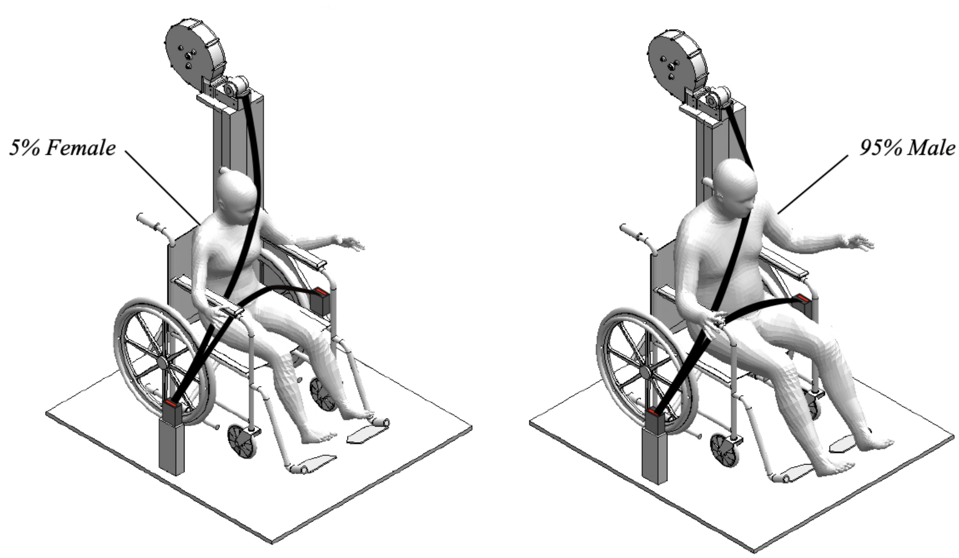


Figure 49: Virtual modeling of belt fit for physiological user range of 5% female to 95% male.

This virtual method was chosen due to the resource demand of physical user testing. Importantly, we assume dimensional accuracy of the CAD modeling and that the standard belt length will accommodate the large anthropometric user range. Thus, limitations of this verification method include the questionable accuracy of a purely virtual model (as opposed to realized physical dimensions) and reliance on individual user observations that may not represent all body sizes.

Industry standard belts and buckles have been used that are traditionally compliant with safety standard FMVSS 209, which mandates crash-appropriate belt and buckle strength. Because this work is fundamentally centered around user accessibility — and the drag chain presenter will not fall in the load path of the seatbelt if there were a crash — this safety testing of the seat belt assembly has been deemed to be out of scope for this project.

Accessibility. Due to the human-centric nature of the design problem considered in this work, there is comparatively more emphasis on the accessibility-focused requirements and specifications. As mentioned previously when outlining the project's relevant requirements (refer to p. 11), high priority is placed upon achieving the specifications related to the design's ease of use because they represent the fundamental motivation for this work. Particularly for the presenter mechanism, focus is directed at the efficacy of the design to meet the dimensional specifications previously outlined. Table 12 presents the relevant accessibility requirements and the associated verification test methods, with the results of testing.

Table 12: Verification plans to address accessibility related specifications, with associated justification for testing.

REQUIREMENT	SPECIFICATION	TEST METHOD	RESULTS
Easy to reach and pull restraint	· Grab point dimensions: · A: ≤ **255 mm** · B: ≥ **572 mm** (beyond 95% male frontal plane) · C: **(230 - 1370) mm**	*Measurement of rig, virtual tests*	· Grab point dimensions (Figure 50): · A = **175 mm** · B = **587 mm** · C = **1114 mm**
	· Belt retraction force ≤ **8 N**	*Measurement of retractor*	· Retraction force = **7.1 N**
	· Can be reached when adorned with winter coat(s)	*Physical testing*	· Qualitatively easy to reach when adorned with coats
Easy to see	· Visual color contrast ratio of **4.5:1** · 50 minutes of arc of visual field of view · 5-point Likert scale score ≥ **4.0**	*Color code relative luminance* *Photo comparison from user view* *Stakeholder validation survey*	*Pending future verification*

One of the most important requirements to test includes the "easy to pull and reach restraint", as the presenter design is focused mainly on this accessibility need. The dimensional specifications within this requirement have been verified with measurements of the test rig, as well as virtual tests and measurements of the CAD models. These methods were chosen due to their simplicity and ability to easily define the field of reach. The only assumption in this case is the location of the wheelchair and user in relation to the exit point of the belt, based on the dimensions provided from GM and Cruise. The limitations of this method include the accuracy of the testing rig, and location of the wheelchair inside of the rig. CAD measurements shown below in Figure 50 serve as verification that the specifications established in the early design process have been met.

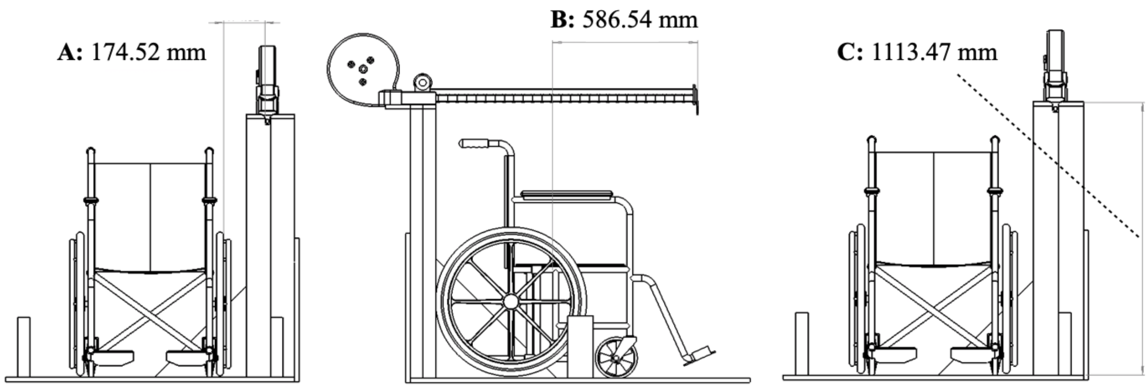


Figure 50: Dimensions of the test rig to verify "easy to reach and pull restraint," grab point dimensions A, B, and C, respectively. All fall within the specification distances, and the "B" dimension is at full presenter extension, showing that it is in front of the 95% male body type that was targeted.

To simulate the user experience of limited upper body mobility, able-bodied test subjects were adorned with multiple winter coats, and the ability to reach and grab the restraint when limited in motion was qualitatively recorded. The presenter was shown to greatly aid reach, enabling users to grab the belt when they otherwise could not reach it. Further user testing would prove very valuable in further substantiating the legitimacy of the design to meet this specification, but resource limitations favored this easier approach. Additionally, force testing of the retractor confirms compliant retractor tension per FMVSS 209 [48], as measured using a force gauge.

To verify the "easy to see" specifications, the extensive use of digital photos of the seat belt assembly is necessary. However, reasonable lighting and accurate color sampling can prove difficult without installing the prototype in the actual rideshare environment. Thus — motivated by the limitations of a purely virtual test — we have planned for this visual testing to be completed inside of the Cruise vehicle, as the color contrast is highly dependent on situational lighting conditions (negating the legitimacy of a virtual test). GM and their accessible engineering team may decide to pursue this verification method in their own review of the design. This decision is substantiated in the context of this project because the scope has narrowed to primarily focus on wheelchair users with limited upper body mobility (rather than addressing vision and dexterity impairments too). To conduct the necessary testing to verify these specifications, photos of the presenter assembly need to be taken within the cruise vehicles. Hex codes could then be identified from photos of the test rig, enabling estimation of the color contrast ratio. Visual field of view of the user can then be verified using user view degrees of arc comparisons against the relative sizing of the presenter assembly within the vehicle interior. Though deemed out of scope in the context of this project, verification of the visual accessibility of the design is admittedly an important step towards generating a holistically accessible product.

Ease of Integration. Ease of integration is an important group of specifications to broadly understand design practicality. As shown in Table 13, verification of these specifications will be completed using measurements, the bill of materials, and the CAD assembly data.

Table 13: Verification plans to address ease of integration specifications, with associated justification for testing.

REQUIREMENT	SPECIFICATION	TEST METHOD	RESULTS
Compatible with existing wheelchairs	· Accommodating to maximum wheelchair size of: · (L x W x H) = **(1068 x 712 x 915) mm** · *Not necessarily cantilevered arms* · Seat height: **(430 - 510) mm**	*Measurement of test rig, virtual tests*	Accommodating to *closed armrest* wheelchairs of (Figure 51): · (L x W x H) = **(1068 x 712 x 915)** mm Seat height = **454 mm**
Compatible with existing vehicles	· Maximum footprint of: · (L x W x H) = **(1100 x 810 x 1060) mm**	*Measurement of test rig, virtual tests*	Footprint of: · (L x W x H) = **(655 x 805 x 1050)** mm
Durable	· Ability to withstand **50,000 cycles** · Ability to withstand anticipated vertical loading force of **16.5 N** at full extension	*Thorough cycle testing out of scope* *Experimental loading of scale chains*	*Pending future verification* Able to support equivalent vertical end load force of **32.2 N** at full extension
Cost	· ≤ **200%** of traditional seat belt assembly cost (i.e. ≤ **$387.28** [97])	*Bill of Materials*	Total cost of **$297.55** (refer to Appendix I)
Ease of assembly	· ≤ **200%** of traditional seat belt assembly steps	*CAD data and manufacturing plan*	Fail; chain manufacturing labor intensive. Refer to p. 70 for suggested changes
Comfortable	· Inner belt intrusion ≤ **10 mm**	*Virtual CAD measurement*	Inner belt intrusion = **5 mm**

Compatibility with existing wheelchairs has been verified by virtual interference measurements with the largest existing wheelchair dimensions present in the current market [55]. The results of this verification are depicted in Figure 51, page 56, with the blue box representing the maximum wheelchair dimensions provided in Table 13 (i.e. L x W x H = 1068 x 712 x 915 mm). This method was chosen due to its simplicity and ability to readily show the compliant wheelchair geometries. The major assumption in this case — much like the proper belt fitment requirement — is the location of the wheelchair and user in relation to the location of the belt, as based on the dimensions provided from GM and Cruise [84]. The limitations of this method include the accuracy of the testing rig and the CAD model in relation to the Cruise platform. Similar virtual measurements of the CAD models and the physical test rig also verify the maximum footprint of the assembly. Note that the buckling locations are included in the system footprint, as the 2-stage buckling architecture is central to the solution concept, even though the presenter itself has a very minimal footprint.

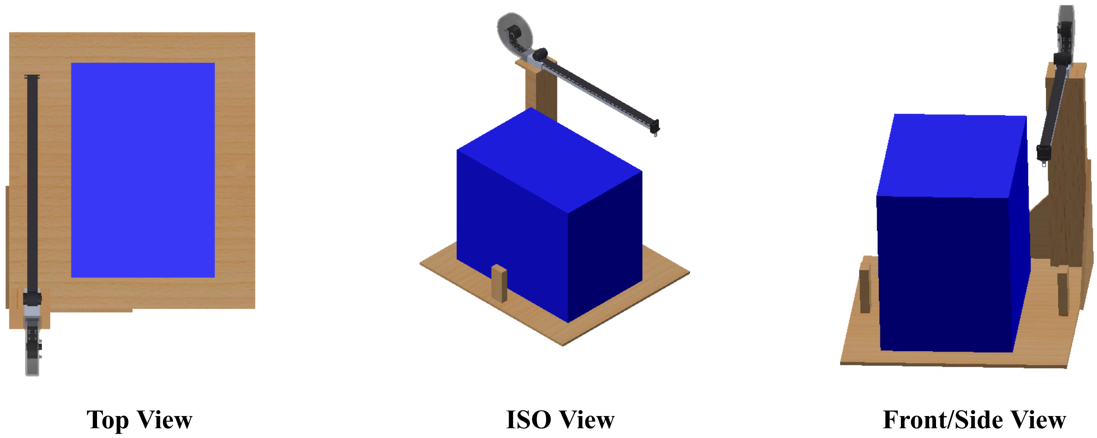


Figure 51: Largest wheelchair dimensions in test rig CAD, verifying that there is sufficient room to maneuver a wheelchair and follow the 4 step buckling process (i.e. *reach/grab/route/buckle*).

In the scope of this work, there is no opportunity to thoroughly analyze the 50,000 cycles of durability required per FMVSS 209 [48]. There are many components in the complete presenter system, and an exhaustive failure modes and effects analysis (FMEA) would be intractable given the tight project timeframe. However, the prototype components are made of materials sufficient to withstand proof of concept testing. This is substantiated by the rigorous empirical testing that was conducted on scale drag chain elements (refer to Figure 33, p. 41), with the anticipated load previously calculated (p. 39) now included as a specification. Destructive testing of the presenter assembly would prove useful in further characterizing the ultimate strength of the system, but destroying the presenter is not feasible given the realized development time and costs. However, experimental loading of the seat belt presenter at full extension with a vertical 16.5 N force (as measured by a hand held force gauge) did not result in any permanent deformation of the drag chain, thus verifying strength of the full assembly in the vertical direction. Further experimentation is necessary to characterize strength and failure in the horizontal direction, though initial testing on the scale chain prototype suggests the horizontal strength is significantly greater than the vertical strength (refer to Figure 30, p. 38)

The cost of the prototype system proves to be less than 200% of the traditional seat belt costs at market prices. A comparable seat belt to those used in GM vehicles costs $193.64 with savings that put it below the OEM retail price [97]. According to the prototype bill of materials, with a total cost of $297.55, the cost can be verified to meet the specification (≤ 200% of traditional seat belt assembly cost). This method can be justified because it uses the true costs of the actual prototype, which will likely be more expensive than the mass manufactured product. One assumption in this method of verification is that it assumes that the materials used in the prototype will be comparable in price to the materials used in the production product. However, this assumption has been deemed appropriate as the production drag chain will likely involve injection molding and therefore cost less than the costly aluminum used in the prototype. Thus, it is reasonable to assume that — at economies of scale — the production part will be less than the prototype. Another consideration that will need to be addressed is the labor costs for the assembly of the production presenter, which will increase the overall costs. As discussed next, these costs are anticipated to be non-trivial due to the assembly demand of the prototype design. Rigorous analysis of the prospective assembly labor costs, however, proves out of scope.

The ease of assembly of the prototype has been evaluated by referencing the manufacturing plan (refer to Appendix II), as well as through the hands-on assembly process. Because the chosen drag chain architecture necessitates the use of many individual rivets and washers (152 of each to be exact), the current labor demand of the prototype assembly is impractical for production at scale, and fails to meet the ease of assembly specification. However, significant changes in production method have been identified (refer to Suggested Changes for Commercial Implementation, p. 70), and it is unlikely that at-scale production will prove intractable if further effort is made to refine the method of manufacturing.

Inner belt intrusion has been verified by measurement of the proposed grab handle design (originally presented in Figure 15, p. 27). As the project focus narrowed to addressing reach via the drag chain presenter, fabrication of the grab handles fell out of scope. However, there is substantial reason to believe that such a design would prove helpful and unobtrusive for users with limited hand dexterity, based on existing product benchmarking [76].

Overall, the design and prototype are compliant with the tested specifications. As periodically mentioned throughout the preceding discussion, further verification in key areas that fell out of project scope due to time constraints will need to be completed by GM and Cruise if they seek to further develop the design solution proposed in this work.

Validation Plans and Results

The design task considered in this work is incredibly human-centric, necessitating the completion and/or planning of extensive validation, discussed at a high level in Table 14.

Table 14: Validation plans to address remaining human-centric specifications, with results (if found).

REQUIREMENT		SPECIFICATION	VALIDATION METHOD	RESULT
Accessible	**Easy to buckle and unbuckle**	· Able to be secured / released with oven mitts · Release force ≤ **21 N** · Insertion force ≤ **52 N** · Buckle guide ramp ≥ **10 mm** fore/aft, ≥ **5 mm** side · 5-point Likert scale score ≥ **4.0**	*Measurement of buckle components in prototype* *User Testing* · *Sympathetic tests with oven mitts* · *In-situ testing with anticipated users*	*Pending future validation:* Rigorous analysis and fabrication of grab handles and funnel buckles previously determined to be out of scope

Table 14: Validation plans to address remaining human-centric specifications, with results (if found).

REQUIREMENT		SPECIFICATION	VALIDATION METHOD	RESULT
	Intuitive	· Time to secure ≤ **1 minute** · Steps ≤ **6** · Can be secured **independently** · 5-point Likert scale score ≥ **4.0**	*Demo/Trial/User Testing* · *Set up full test rig* · *Use armed chair for non-wheelchair users*	*More validation necessary:* Initial testing with test rig and able bodied subjects found **independent** securement possible in **under 1 minute**
Easy to Integrate	**Socially inert**	· 5-point Likert scale score ≥ **4.0**	*Validation surveys with GM Able*	*More validation necessary:* Single Likert scale response of 3.0

The nature of the problem — *an accessibility device for wheelchair users* — invokes the need for surveys, demonstrations, user trials, and holistic evaluation. A large portion of the design approach involves how a user interacts and uses the system, which has been integral to our sequential progression through concept ideation, selection, analysis, and final design. Thus, the stakeholders are key to the success of this project, and without their input and feedback, the solution would likely be incomplete and have more obstacles in usability.

As previously mentioned, the user is essential to the success of the project, so preliminary validation work has been completed. We presented at a GM Able Resource group meeting and some initial feedback. Following this presentation, we asked for more written and trackable feedback on the complete presenter system and the social metrics more thoroughly defined in the requirements. Presently, we have not yet received feedback from GM Able, but we have created and released a form, noted in Appendix III. We also sought out an expert evaluation from UMTRI with a researcher or doctorate who specializes in the accessibility industry. These results from Dr. Klinich of the UofM Travel Research Institute are detailed in Appendix IV, but can be summarized to a few main points. Dr. Klinich ranks the presenter as a 3.0/5.0 for social inertness, but there are many other confounding factors that she identified. She also mentioned that the system seemed fairly intuitive, with the condition there was some instruction on the autonomous vehicle before it arrived. Lastly, Klinich identified a few issues with the ability for the system to be independent, mentioning her experience with UMTRI. Buckling and unbuckling was also identified as a problem, and that making the system operable with a fist would be beneficial. All of this feedback is very valuable, especially from a subject matter expert like Dr. Klinich. Overall, for the timing and scope of the class, Dr. Klinich was highly impressed with the solution, and had only suggestions to further improve the accessibility of the design.

As described in Table 14, a significant amount of validation remains necessary to evaluate overall design efficacy. Initial testing with the presenter test rig and able-bodied subjects suggested promising results for independence and time for securement. However, further analysis and design iteration is necessary to develop the ancillary system components that fell out of project scope (i.e. the grab handles and funnel guided buckles, refer to p. 27) and further validate those subsystems. If further development of this project is desired by GM and Cruise, it is recommended that extensive user testing is conducted with wheelchair users wherein the full four-step process of reaching, grabbing, routing, and buckling is analyzed. This will aid identification of potential pain points with the system, and more importantly, will uncover how users interact with the system. Further work could evaluate the learnability of the presenter system with no prior experience or design focus, and attempt to understand the efficacy of the system from the user perspective. Such a validation effort could help identify and assess the frustrations of the system, and motivate changes for the final product. In depth validation of the design could follow the process outlined in Appendix V**.**

DISCUSSION

Having traversed the design process from problem definition through to a functional prototype solution (refer to Process Model, p. 6), an honest critique of this work is now discussed. First, we comment on the definition of the problem that motivated this work, reflecting on what questions and needs might have been overlooked. Then, a critique of the final prototype is presented, noting key challenges in the design that need to be addressed in future iteration. Finally, this section concludes with a discussion of the challenges encountered during the course of this work, and what risks remain outstanding.

Problem Definition Critique

Due to the inherent social and functional complexity of improving transportation accessibility, this work has made a significant attempt to define the underlying problem and understand the needs of the target user group. As aforementioned in Project Motivation and Current Accessible Restraint Systems (p. 3-6), notable efforts were made to consider the problem from a variety of angles (i.e. functional, social, and economic) to generate a holistic problem perspective. The information gap between the target demographic and us (the engineers) as it pertains to wheelchair user needs/difficulties was identified clearly and early, and thus significant input was sought from relevant stakeholders (such as wheelchair users [27], disability researchers [28], and industry experts [54]). In general, there was a deliberate intention to let the research and user input drive the development of this project, and abstain from superimposing our preconceived judgment and ideas too early in the process.

Despite these best efforts, this project was completed in a fairly tight timeframe, and it would be negligent to pretend a fully complete problem understanding was achieved. This problem space involves not only a highly regulated environment where safety is a primary concern, but also encompasses a myriad of nuanced social and human factors. For instance, one of the requirements considered in this work was "social inertness," which is meant to capture how inconspicuous a design is so as to prevent the user from feeling out of place in a shared environment. From a purely technical perspective, this requirement would be incredibly easy to overlook; it only emerged as an important consideration following our conversations with wheelchair users. Thus, there are likely a number of similarly elusive user needs/perspectives that were simply missed in the background research that motivated this project. If given more time and resources, it therefore follows that additional user input would be a desirable asset in furthering the depth of problem definition. This extended research could take the form of user studies or more interviews, with the central goal being to probe deeper into the underlying user needs that are hard to elucidate from a surface level perspective. Ideally, we could observe how wheelchair users interact with current restraint systems, and try to uncover subtle deficiencies in current solutions that might not arise in conversation. This additional information could prove immensely valuable in guiding meaningful design changes that better reflect user needs.

In critiquing the development of this project, it is also worth reflecting on how prospective solutions were filtered and selected. As mentioned previously when discussing the final concept (refer to Commentary on Selected Concept: Fixation and Influence, p. 24), the scope of the solution space was quickly narrowed to belt-style restraint systems. Though there was notable motivation to do so as driven by regulations, part availability, and industry wisdom, we explicitly mentioned that the project timeframe was also a significant influence on this decision. Exploring and rigorously developing more novel solutions (such as a rollercoaster style harness or an active inflatable restraint, refer to Figure 8, p. 18) was simply determined to be intractable in the semester-long window of this work. However, these concepts might address user needs better than the chosen concept if given further consideration, or at least possess some aspect of merit that could inform useful design changes elsewhere. Thus, further consideration and development of the solution space would likely be a useful exercise in promoting solution efficacy.

In general, we feel that the problem definition and concept exploration presented in this work are appropriate reflections of the time and resource limitations present in this project scope. Best practices were identified and incorporated early into the project development, and deliberate efforts were made to sustain these practices as the work progressed. However, we also recognize that the nuanced, human-centered nature of the underlying problem necessitates a truly rigorous exploration of user needs, and further work would likely uncover new insights.

Prototype Design Critique

As previously discussed during concept selection (Pugh Matrix Analysis, p. 23) and substantiated by the verification and validation results (Verification and Validation, p. 51), the functional prototype presenter created in this work possesses desirable properties pertaining to accessibility, adaptability, and packaging size. Specifically, the design has been shown to accommodate a variety of different user needs, body types, and wheelchair geometries, all while requiring a comparatively smaller package than existing presenter benchmarks [2]. However, as previously mentioned when discussing the verification and validation testing, the prototype design faces unanticipated issues with binding of both the drag chain and the seat belt itself during deployment of the system. In particular, the drag chain binds internally within the presenter housing, while the seat belt binds within the presenter end plate when pulled at an angle. Unfortunately, we believe that the internal binding of the drag chain is a fundamental consequence of driving the nested system from the central spool, and thus requires more than a simple reduction of friction or geometric change to amend. The binding is believed to be a product of both the exponential decay of the pushing force between adjacent chain blocks as frictional losses compound, and specific instances during deployment wherein blocks are geometrically loaded in a manner that locks them in place (similar to a doorstop). These theories are discussed and developed further in the following sections. Finally, this present design critique concludes with a commentary on the seat belt binding during presentation, and the implications of this phenomenon on the overall system operation.

Force Decay via Inverse Capstan Equation. To gain intuition about how the extension force is transferred between adjacent blocks, we presently develop a relatively simple model that includes parasitic friction losses between the chain blocks and the presenter housing. The Capstan equation — which describes the increasing torque that can be borne by a spooled rope as friction compounds [98] — is referenced to inform model derivation. Crucially though, the geometry of the drag chain loading is directionally opposite that described by the Capstan equation (with an outward radial expansion as the chain presses against the interior of the housing rather than an inward radial constriction as a rope wraps around a spool). Consequently, the differential chain element used to construct the model is loaded in compression rather than tension, with an inward normal force arising on the chain from the presenter housing. A free body diagram of this model with the relevant differential variables is presented in Figure 52.

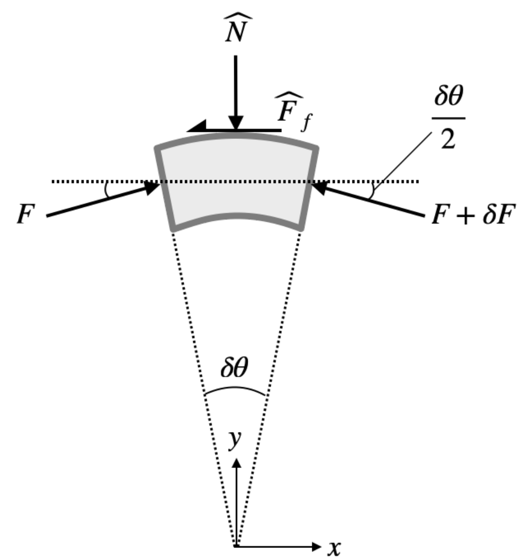


Figure 52: Inverse Capstan free body diagram.

To develop an equation for the force between adjacent chain blocks (F), the free body diagram of Figure 52 can be used to sum forces in the x and y directions in Eqs. 15 and 16 as:

$$\Sigma F_x = 0 : F cos(\delta\theta/2) - (F + \delta F) cos(\delta\theta/2) - \widehat{F}_f = 0 \tag{15}$$

$$\Sigma F_y = 0 : F sin(\delta\theta/2) + (F + \delta F) sin(\delta\theta/2) - \widehat{N} = 0 \tag{16}$$

where $\delta\theta$ is the differential angle element, $\widehat{F}_f$ is the length-normalized frictional force, and $\widehat{N}$ is the length-normalized normal force. Recognizing the linear relationship between normal force and friction via the coefficient of friction (μ) and that the cosine and sine of an infinitesimal angle is equal to 1 and the angle itself [99], respectively, these equations can further be simplified into Eqs. 17 and 18 as:

$$\delta F = \widehat{F_f} = \mu \widehat{N} \tag{17}$$

$$F\delta\theta = \widehat{N} \tag{18}$$

Using $\widehat{N}$ as a common variable to combine Eqs. 17 and 18 yields the following Eq. 19:

$$\frac{1}{F}\delta F = -\mu\delta\theta \tag{19}$$

which can finally be integrated to solve for the pushing force between adjacent block chains (F) as a function of the amount of angular spooling (θ) in Eq. 20 as:

$$F(\theta) = F_0 e^{-\mu\theta} \tag{20}$$

where F_0 is the initial force on the first block element in the chain. Immediately, it is clear that the equation takes the form of exponential decay, meaning that the pushing force between adjacent blocks is predicted to sharply decrease as the amount of coiled spool increases. To understand the implications of this model for the prototype presenter, we can recognize that the drag chain coils around two and a half times when fully retracted (i.e. $\theta = 5\pi$ radians). Then, using an experimentally measured coefficient of friction of $\mu = 0.27$ (as measured in a setup similar to Figure 32, p. 40), the force acting on the last drag chain is predicted to be just **2%** of the force exerted at the center of the spool (i.e. $F(\theta = 5\pi) \approx 0.02F_0$). This suggests that there is a truly significant reduction in pushing force as the effect of friction compounds over the length of the spool. Any small increase in friction or slight catching of the end of the chain (such as when sliding over the rivets) could potentially be enough to bind the whole mechanism, even if the motor is exerting a significant torque. Thus, this model provided useful insight into how a relatively small frictional force can have exponential effects on the required extension force for the chain when centrally driven.

There are of course some major assumptions that aid the construction and use of this model. Most notably, we have ignored the changing frictional interface and geometry as the spool coils on top of itself; instead, we simply assume that the chain is coiled with a constant curvature and interacts only with the ABS presenter housing. Despite this simplification, we believe this is actually a conservative assumption that underestimates the magnitude of friction, as sliding over the protruding rivets and washers would likely introduce an even higher coefficient of friction. Furthermore, this analysis is simply intended to gain an intuitive understanding about how the frictional force scales within the presenter internals. Recognition of the exponentially decaying nature of the pushing force alone is sufficiently informative for guiding this prospective commentary on the binding phenomenon.

Block Jamming via Doorstop Geometry. Through repeated testing of the presenter deployment, it became evident that the chain frequently binds in specific and consistent locations during extension. In such locations, the force on a certain block element acts in such a way as to wedge the block in place, similar to a doorstop. To further understand how this jamming mechanism arises, we presently employ a simple free body diagram model of an individual chain block, informed by the geometry of the chain when in a seized position. Figure 53 depicts the configuration of the chain when jammed, and the relevant free body diagram used to model this situation. Notably, the force between adjacent blocks is assumed to be a point load acting through the pivot joint, and parallel to the inciting block element. A normal force (and associated friction) are then assumed to arise at the interface of the block and the interior of the presenter housing. In a method similar to that used in the previous section detailing the exponential force decay, summing the forces in the x and y directions yields Eqs. 21 and 22 as:

$$\Sigma F_x = 0 : F cos(\theta) > F_f = \mu N \tag{21}$$

$$\Sigma F_y = 0 : F sin(\theta) = N \tag{22}$$

where F is the applied force between blocks, θ is the angle of the applied force, N is the normal force, F_f is the force of friction, and μ is the coefficient of friction. The inequality in Eq. 21 reflects the fact that the component of the applied force in the x direction must be greater than the force of friction or else the mechanism binds. Combining Eqs. 21 and 22 using N as a common variable leads to an elegant constraint on the coefficient of friction μ per the angle of the applied force θ in Eq. 23 as:

$$\mu < 1/tan(\theta) \tag{23}$$

For the seized geometry indicated in Figure 53 (i.e. θ = 76.5º), Eq. 23 stipulates that the coefficient of friction **μ must be less than 0.24**. This value is less than the coefficient of friction we experimentally estimated for the interface between the elastic cord and ABS housing of 0.27, correctly predicting that the block wedges in place.

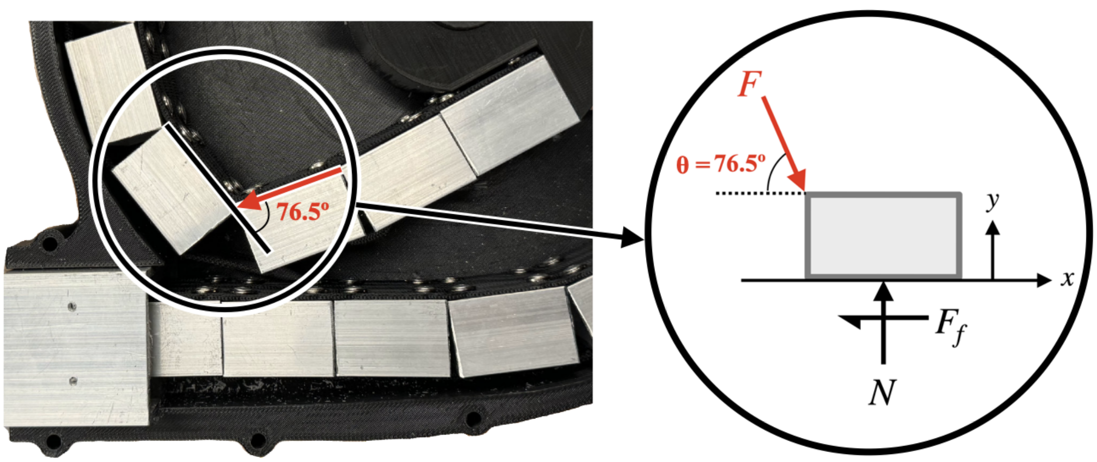


Figure 53: Seized geometry of the prototype chain mechanism (left) with associated free body diagram and relevant forces (right) to describe the binding scenario.

In summary, we believe that the drag chain binding phenomenon is a product of the coupled influence of an exponential decay of the pushing force (via the inverse Capstan model) and the wedging of the blocks (via a doorstop-like jamming geometry). Though potential reductions in internal friction might help remedy the severity of binding, these two mechanisms appear to be fundamental limitations of a centrally-driven spool system, and will continue to complicate extension even for low internal friction. Thus, subsequent suggestions for areas of future improvement and work are focused on a more substantial redesign of the presenting mechanism, presented in Recommendations, p. 68.

Compromised Sequence of Operation. As aforementioned, the drag chain binding during extension was not the only unanticipated binding phenomenon; the seat belt also binds when being pulled through the presenter end plate at an angle. Though the presenter end plate includes a curved opening to attempt to account for pulling the belt at an angle (refer to Figure 35, p. 43), this opening proved insufficient for the pull angles necessary to fasten the belt from a wheelchair-seated position. Figure 54 presents a picture of the belt when bound in the presenter end plate for reference.

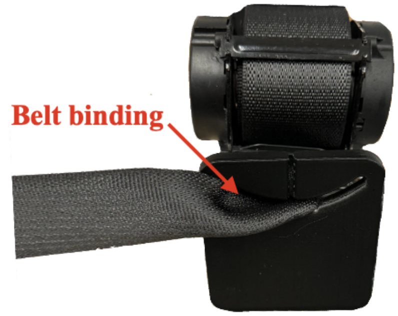


Figure 54: Seat belt bound in presenter end plate.

This binding amplifies the forces experienced by the drag chain, which has a significant impact on the overall operation of the presenter mechanism. Namely, the force required to pull the belt vertically through the end plate (as described in Semi-Empirical Estimation of Operational Belt Load, p. 39) was found to be 2.1 lbs (9.3 N) as measured by a handheld force gauge (close to the previous estimate of 9.68 N). This is the force that — when combined with the weight of the chain itself — informed the design and selection of a chain architecture per Figure 33, p. 41. However, when the belt is bound in the presenter end plate (such as in Figure 54), the force required to pull the belt through the plate jumps up to 9.7 lbs (43.1 N). This ~360% increase in the applied load due to binding is clearly problematic for the integrity of the drag chain; even though the load is not acting purely in the vertical direction, the current chain architecture is simply not designed to support such loads when fully extended. Thus, the sequence of operation of the seat belt presenter had to be modified to isolate the chain from this high pull force. Rather than keep the chain extended throughout the restraint securement (such as described in Figure 19, p. 29), the prototype presenter must be immediately retracted after the user grabs the belt (as described in Figure 39, p. 45). This is a clear loss of functionality and greatly reduces the ease of use of the design; the user must hold their arm out and wait for the presenter to retract until they can begin securing the belt. Placing such a requirement on the user is particularly damaging to design efficiency when the central project goal is to promote ease of use and accessibility. As such, further commentary and suggestions are provided later in Recommendations (p. 68) that might prove useful in remedying this additional binding issue.

Realized Challenges and Outstanding Risks

Through the course of this project, a number of unique challenges arose that had to be appropriately addressed to minimize adverse effects on the final design solution. As previously discussed in detail (refer to Problem Definition Critique, p. 59), properly identifying the needs and perspectives of the target disabled user group proved to be a nontrivial research exercise; over a dozen interviews with wheelchair users, disability activists, and industry experts had to be conducted in a short period of time to generate a suitable understanding of the problem space. This thorough problem definition also brought additional difficulties by creating a wide project scope, necessitating a fairly broad range of requirements that represented a mixture of safety regulations, user needs, and functional sponsor requirements (refer to Table 4, p. 13). To ensure that an appropriate depth of analysis and design embodiment could be achieved, the project scope was later narrowed to simply the presenter mechanism. This decision was motivated by the relative complexity and novelty of the presenter mechanism as opposed to other components in the selected concept strategy such as the buckle funnels or grab handles. The design of the drag chain itself also proved to be a challenge; the geometric complexity and number of potential design variables was deemed too extensive to be thoroughly tackled from a purely analytical perspective given the project time constraints. Instead, an empirical approach was taken wherein a number of scale prototypes were constructed with varying geometry, materials, and fabric securement method, and then compared to a semi-empirical estimation of the anticipated loading (refer to Figure 33, p. 41). Though less informative about the fundamental mechanics and behavior of the chain than an analytical approach, this empirical method enabled a fairly quick and practically meaningful consideration of the chain architecture.

It is also productive to consider the potential outstanding risks to end users of the design developed in this work. Of course, the unresolved binding of both the drag chain and the seat belt remain troublesome for design efficacy. The current sequence of operation is unintuitive and physically difficult for users, subverting the ultimate project goals of accessibility and ease of use. Remedies for these binding issues (discussed in Recommendations, p. 68) must be identified and enacted before any true implementation of the design is possible. Additionally, the use of two separate latch plates is a unique aspect of the design that requires further validation. Significant questions remain surrounding the learning curve to use such a restraint in a foreign rideshare-like environment, and safety concerns persist around improper use. It is possible that an uninformed user could incorrectly secure the belt in a dangerous way without knowing it (such as only having only one of the buckles secured). This could potentially be addressed with color coding and latch plates that are only compatible with the relevant buckle locations (or perhaps a mandatory initiation video distributed via the Cruise Origin vehicle app), however further work is necessary to better understand the status of this design component and address the associated risks. Finally, the strength of the drag chain is still a potential concern in the context of the demanding environment of shared transportation. The structural integrity of the chain could potentially be compromised if a particular user acts rough with it, or even if it was unintentionally bumped into. Further work to develop a commercially robust and production scalable drag chain architecture remains necessary.

REFLECTION

The comprehensive goal of this project was to improve the lives of wheelchair users, as transportation remains a difficult and weighty issue. With projects and work like ours, hopefully we are able to become one step closer to full accessibility for wheelchair users.

Context and Greater Impact

The project has a great impact on public health, welfare, and safety for both the presenter's users and the people around them. The presenter and buckle system allows the wheelchair user to access the seatbelt in the Cruise Vehicle, which allows the user to restrain themselves. During stakeholder interviews in the early stages of the project, wheelchair users explained that the current seat belt configurations were too difficult to manage or not safe enough to use. Using the seat belt presenter system, proper seat belt configuration can be achieved which will provide a safer ride and therefore have a positive impact on public safety and welfare. The system will provide users with previous barriers to transport a way to interact more freely, in a safe way. Additionally, in a shared autonomous vehicle, a properly restrained wheelchair user will also have public safety benefits for other passengers in the event of a crash scenario.

The design will impact the global marketplace because barriers for disabled people exist all across the world, through many different industries. By bringing the seat belt presenter to the global marketplace, these barriers will be lowered for disabled people. Eliminating transportation barriers could boost the economy by 4.4 million workers and $867 billion per year [13], which would have an impact on the global economy.

To identify the social impacts of the manufacture, use, and disposal of the final product, it is important to investigate the final materials and manufacturing processes of these parts. For the final design, the outer casing will be made out of injection molded plastic, and the drag chain will be injection molded onto seat belt webbing. The electric motor will have a control module which will be made up of electronic components, integrated into the Cruise Vehicle. For the injection molded plastics, they could have social impacts in the communities in which they are manufactured. Exposure to plastic fumes is a major problem which affects those that work in plastic manufacturing. Additionally, for the production of the motor and control modules, the metals used in electronics manufacturing have vast social consequences, such as displacing communities and affecting local drinking water of impoverished communities.

The final product will have economic impacts associated with the manufacture, use, and disposal. For the manufacturing of the product, many local economies can be affected both positively and negatively. For example, for the manufacturing of the casing and drag chain, Cruise will likely contract work from other companies in different parts of the world to injection mold these parts. This can benefit smaller local economies. The use of the product will affect the economy by allowing a large section of the population, namely the disabled, to have easy and reliable transportation. This will allow handicapped people to go to work and participate in society in a way that has not been easily accomplished before. This will have a positive impact on the economy where the seat belt presenter is introduced.

In order to evaluate the ecological and societal impacts of the product, the team used stakeholder analysis to measure how the product will affect wheelchair users. Additionally, the team performed simple life-cycle analysis at the beginning of the project to determine what the ecological impact of the final production product will be. It was determined that the life cycle of the presenter system would not significantly impact the life cycle of the vehicle and standard seat belt.

Impact of Culture and Identity

Amongst our teammates, cultural, privilege, and identity played a role in the approach that was taken for the project. For the most part, the similarities in these areas allowed the team to be cohesive in the design process. The biggest impact came from stylistic differences between the group members. The differences in the styles of the group members allows for different perspectives that were useful throughout the project.

Differences in culture, privilege, and identity between the teammates and the sponsor influenced the design process in both a positive and negative way. One major difference in identity between the teammates, sponsor, and stakeholders was the understanding of the experience of disabled persons. Each of the members of the team for the project are able bodied, so understanding the culture, identity, and lived experience of disabled people was very important. The team needed to understand that their experiences would never mirror those of the wheelchair users, and this was essential to be cognizant of throughout the process. This difference likely was both positive and negative for the project. It was positive because it offered an outside engineering perspective, but negative because of the lack of knowledge of the disabled community, and what it means to use a wheelchair in daily life. Power differences between the group members and the sponsor also played a large role. The sponsor was heavily involved with the project, often having significant influence in it. That said, the ideas of the sponsor were given special attention, as he had substantive background in the accessible industry. This caused the sponsor to have a large impact on the final design and execution of the project.

Inclusion and Equity

There was a power dynamic that existed between our group and some of our stakeholders. All four of our team members are able-bodied people who have never used a wheelchair or helped a wheelchair user in a vehicle. Many of our stakeholders were either wheelchair users or caregivers, who have first hand experience with the given problem. This proved to be very helpful for our project because they were able to guide us in the right direction. As a group, we placed additional emphasis on the stakeholder's opinions, past struggles, and guidance for the concept generation phase of the project. As we slowly entered the design and manufacturing stages, we used our own ideas built on our stakeholders', introducing an inherent bias for our designs. Our group and our direct sponsor had first hand experience with all of the technical problems with the project, so it made more logical sense to pursue our concepts, built on the empathy interviewing and stakeholder input, at this stage.

Ethics

One important ethical dilemma we faced was creating a socially inert design. While safety was our first priority when designing the prototype, we wanted to ensure that the wheelchair user also feels comfortable using it. Our goal was to create a prototype that was low profile but also fully functional and in accordance with our requirements and specifications. In order to address this dilemma, we met with many stakeholders to gather their opinions. Whether it was a wheelchair user or a caregiver, everyone that we met with gave valuable feedback. Their perspectives were crucial, as our group had very little prior experience with managing wheelchairs or restraints in a vehicle.

Our project was first outlined with many disabilities in mind, and was quite broad. As we worked with our sponsor and mentor, we were able to design with a very specific set of disabilities in mind. It worked well for our class, but if the project were to enter the global marketplace, new problems would likely arise. This being that specific disabilities vary greatly between each user making it very difficult to create one solution that would work for everyone that would be possibly using the system.

Even though this project is meant to be an affordable solution for transportation for wheelchair users, it is not free. Certain wheelchair users might not be able to afford the service, with it being an autonomous vehicle system. Our goal is to improve the accessibility for all wheelchair users, but this might prove to be difficult.

Our personal ethics are very similar to ethics we expect from the University of Michigan and future employers. We recognize that honesty, integrity, and responsibility are crucial in both the personal and professional realms. We believe to treat everyone with respect and to value diversity. Similarly to the goal of this project, we work towards creating a more inclusive and accessible environment for all similarly to how the University of Michigan and any future employer would too.

RECOMMENDATIONS

Motivated by the shortcomings identified for the prototype presenter (refer to Prototype Design Critique, p. 60), this section provides recommendations for future work to improve the design. Namely, prospective remedies for the drag chain and seat belt binding are presented, based on the realized failure behavior of the physical prototype. This section then concludes with a brief discussion about potential changes that could aid robustness and scalability in the hopes of future commercial implementation.

Prospective Binding Solutions

As previously discussed, the internal binding of the drag chain is thought to be a product of both an exponential decay in pushing force between adjacent blocks (Figure 52, p. 61) and instances of jamming geometries wherein individual blocks are loaded in a manner similar to a doorstop (Figure 53, p. 63). Though both of these phenomena are fundamentally a consequence of internal friction, we believe an effort to simply reduce friction between the internal components will be insufficient to remedy the issue; the phenomena are believed to be an inherent consequence of driving the drag chain from the centrally located spool. Thus, any small increase in friction as the product wears (or potential snagging between the interface of layered blocks in the chain) would likely lead to binding. Because the drag chain extension is wholly necessary for the design to be useful — and because this product is intended to operate in a relatively harsh environment (shared transportation) — any suspicion of binding over the product lifetime is unacceptable. A more robust solution is needed.

As the realized chain binding is believed to be an inherent consequence of the centrally driven spool, it follows that changing the location of the motor drive could prove useful in resolving this issue. In particular, we believe that relocating the motor to the mouth of the presenter is a potential design iteration worth further investigation. This idea is substantiated by both industry benchmarking and physical testing of the prototype presenter. Specifically, a similar class of products (known as "zip chain actuators" [100]) use a mouth-drive sprocket to extend and retract a coiled metal chain. Though these products are designed to handle axial (push/pull) loads along the length of the chain (rather than the horizontal, cantilever style loads of the seat belt presenter), there are a significant number of similarities with the presenter design considered in this work. Thus, this industry reliance on a mouth-drive configuration is likely useful wisdom for how to drive such a coiled chain geometry. We also conducted a relatively simple experiment with the prototype presenter wherein the motor was detached from the central drive spool, and the force required to pull the chain out of the housing from the mouth of the presenter was measured using a handheld force gauge. This extension force was experimentally determined to peak at just 2.6 lbs (11.6 N), suggesting that a mouth-drive configuration could be possible for the prototype presenter. Figure 55 provides a high-level prospective schematic of how this design change might be realized.

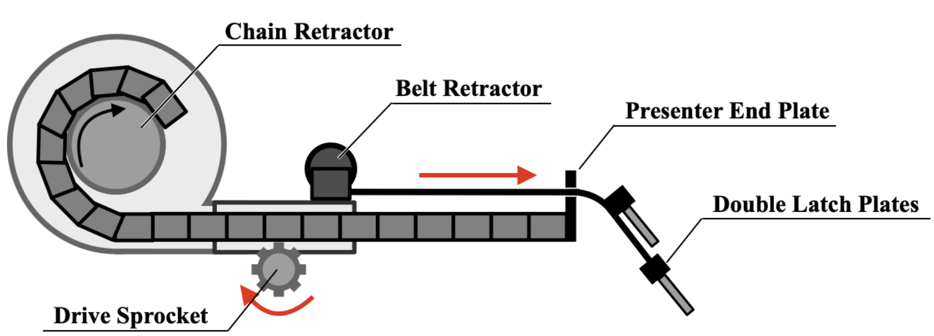


Figure 55: Prospective mouth-drive presenter configuration to resolve chain binding issue.

As depicted in Figure 55, we propose investigating a sprocket-based design wherein the drive unit is located below the support channel. Mating notches could be cut into the chain blocks to interface with the sprocket, and an opening could be made on the bottom of the support channel to enable this interaction. Notably, having the mouth-drive unit helps with extension, but similar binding issues with force decay and block wedging could now arise during retraction (as the chain is pushed back into the housing and forced to coil). To remedy this, we suggest installing a constant-force torsion spring on the original drive spool, effectively making it a "chain retractor" that operates in a similar fashion to the belt retractor. This will tend to increase the amount of torque required at the drive sprocket during extension, but is believed to greatly assist in keeping the chain aligned and away from the frictional interactions with the presenter housing walls that are believed to cause binding. Of course, significant research and engineering analysis is necessary to further develop and characterize the merits of this concept, but our experience with the prototype presenter created in this work inspires confidence that it is a concept worth investigating, should this project be considered for further development.

Resolving the seat belt binding, on the other hand, will likely prove to be a far simpler exercise. As previously characterized (Figure 54, p. 64), the seat belt binds in the presenter end plate when pulled at a sharp angle (such as when securing the restraint from a wheelchair-seated position). To remedy this, the geometry of the seat belt presenter simply needs to be modified to accommodate for steeper pull-angles. This could be accomplished by increasing the arc length of the opening in the presenter end plate, or by introducing a pivot mechanism that allows the end plate to rotate according to the relevant pull-angle. The latter idea (the pivot mechanism) is conceptually depicted in Figure 56.

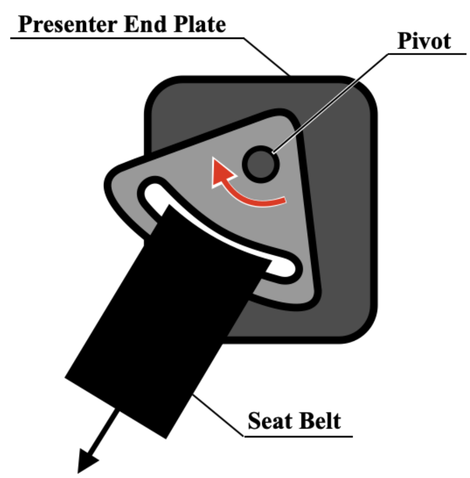


Figure 56: Belt pivot mechanism concept.

Admittedly, the design changes suggested in this present discussion (mouth-drive actuation and pivoting end plate) could likely be implemented without an excessive amount of modification of the prototype model. As such, we originally hoped to investigate these changes ourselves and resolve the unanticipated binding. However, limitations in time and team member availability were simply too great to enact these ideas as the project came to a close. We therefore hope that these recommendations serve as productive motivation for future work on this project concept.

Suggested Changes for Commercial Implementation

In order for this concept to be practically viable for the desired shared transportation context, significant refinement is necessary to increase system robustness and ease of manufacturing. As discussed in Commentary on Build Design (p. 49), many of these changes will likely involve minimal alterations in component geometries and the use of different materials (such as injection molded plastic as opposed to 3D printed ABS). However, the drag chain itself likely requires a more thorough redesign. Though the current design has been verified to support the operational load of a routine belt securement, more strength is desired to ensure chain integrity for potential abuse in a harsh rideshare environment. Furthermore, the current design necessitates an excessive amount of labor and number of parts (particularly rivets and washers) to manufacture. Thus, a more robust construction that lends itself well to production at scale is needed.

Leveraging the tested manufacturing and design wisdom of a mature industry, we believe that employing a design similar to molded rubber tracks used for heavy construction machinery could be a potentially favorable iteration of the drag chain. These tracks use a blend of synthetic rubber compounds with embedded high-tension steel cables to create a pliable (yet fairly inextensible) assembly that can rapidly be produced with hydraulic molds [101]. A cross section track, highlighting the embedded steel cable, is provided in Figure 57.

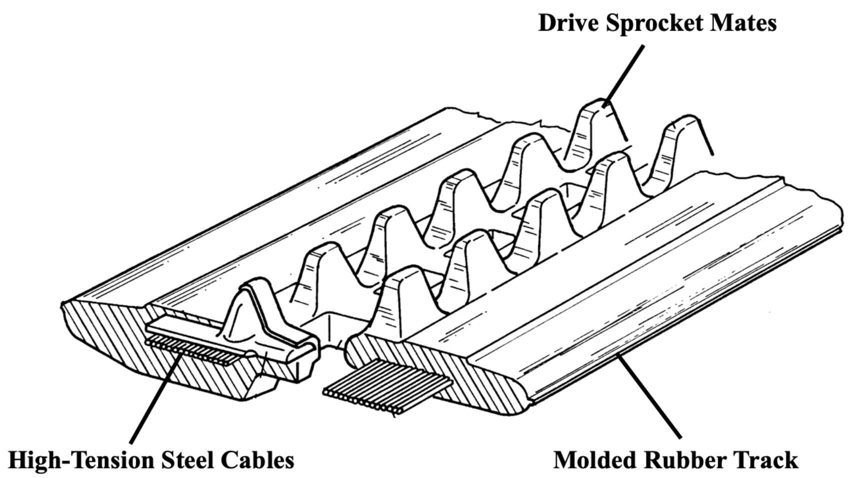


Figure 57: Cross section of molded track with embedded cables, adapted from [102].

In the context of the drag chain considered in this work, a similar configuration with embedded cables could be used to promote chain strength during the restraint securement process. Individual chain blocks could simply be a part of a continuous mold, wherein the rubber compound and steel cables connect chain blocks and allow for relative pivoting. Notably — to get a linear behavior at extension — there should be zero gap between adjacent chain blocks. Thus, a curved mold is likely necessary to allow for full sized blocks to be molded that rest flush against each other (zero gap) when the chain is straightened. Similar to that shown in Figure 57, mating features could be molded into the chain that engage with the proposed drive sprocket considered earlier (refer to Figure 55, p. 69). Such a design could therefore drastically reduce the parts and labor required to fabricate the chain by transitioning from hundreds of components (individual blocks, rivets, washers) to a single continuous part.

Employing a molded construction for the drag chain is presently believed to promote both chain robustness and manufacturability. Specifically, the pliable yet high-tensile strength configuration is thought to be a favorable architecture for the demanding rideshare environment; rather than having rigid aluminum blocks that cause the fabric backing to permanently deform under high loads, this rubber configuration could allow the chain to simply deflect while preserving the structural integrity of the cables. In terms of manufacturing, fabricating such a design is well-established, and knowledgeable experts exist in industry. Finally, a continuous rubber chain would likely prove to be aesthetically favorable, while also improving user safety by moving away from the sharp edges of the aluminum blocks.

Of course, further investigation and engineering rigor is necessary to assess the validity of such an idea and generate a design that is appropriately stiff yet packagable. However, our experience with design and construction of the drag chain presented in this work motivates our belief that such a molded construction could prove productive in future work.

CONCLUSION

As presented herein this report, this work has explored the problem space surrounding accessible restraints in an autonomous vehicle context, and systematically developed, fabricated, and verified a design strategy to address this fundamental need. Significant transportation barriers have been discussed for wheelchair users (Project Motivation, p. 3), and deficiencies with current accessibility benchmarks have been identified (Current Accessible Restraint Systems, p. 4). The project scope — as directed through initial research and sponsor input from GM — has narrowed to wheelchair users with reach impairments. Ultimately, this project has a clear potential for social impact; improvements in transportation accessibility could lead to widespread advancements in employment, education, healthcare, housing, and community life for the disabled [12]. Diligent engagement with relevant stakeholders (identified in Stakeholder Analysis, p. 8) have therefore been central in guiding an effective solution strategy.

Through a combination of benchmarking, stakeholder interviews, literature review, and a consideration of relevant standards, a robust scope of project requirements have been identified and translated into engineering specifications (Table 4, p. 13). Broadly, these requirements fall into 3 categories: *safety*, *accessibility*, and *ease of integration*. Specifications pertaining to *safety* have been informed via elective adoption of the RESNA WC-4 wheelchair restraint standard, while *accessibility* has been specified through product benchmarking, related accessibility standards, and stakeholder input. *Ease of integration* requirements such as compatibility with existing wheelchairs have also been established. To ensure solution viability and user safety, requirements pertaining to safety and accessibility have been considered top priority.

Motivated by benchmarking and project requirements/specifications, a broad scope of occupant restraint concepts have been investigated (Concept Generation, p. 15). The solution space has subsequently been narrowed to belt-style restraints to leverage the related history of rigorous crash testing and safety standards [48], [49]. Within the belt-style restrain domain, further conceptual ideation has been conducted by functionally decomposing the problem based on the sequence of user actions [56]. Focused concepts have been generated within the resulting sub-functions (*reach/grab/route/buckle*), and sequentially combined based on synergistic compatibility to generate total solution strategies. The resulting concept candidates have then been systematically downselected using a Pugh matrix to identify a single strategy for further development (Table 8, p. 23). An 'alpha prototype' of the selected concept — a single belt with grab handles and funnel buckles with a drag chain presenter — has been developed and discussed in detail (Proposed Concept Design, p. 25).

The project scope has further been narrowed to the presenter itself due to the inherent complexity and non-traditional application of this mechanism, and a considerable amount of theoretical analysis and empirical testing has been conducted to inform a final prototype design. Scale prototype chains have been fabricated (Figure 26, p. 36) and strength tested (Figure 29, p. 38) to empirically motivate an appropriate chain architecture. Having selected an aluminum construction with a riveted seat belt webbing backing, a final design has been generated (Figure 34, p. 42) with an associated bill of materials (Appendix I) and assembly plan (Appendix II).

A functional prototype of the presenter mechanism has been fabricated (Figure 46, p. 49), and preliminary verification and validation tests have been completed. Virtual modeling of the test rig verifies design compatibility across a wide range of anthropometric user types (5% female to 95% male, Figure 49, p. 52), and positional measurements of the presenter system have been shown to be in compliance with the targeted reach assist goals (Figure 50, p. 54). Additionally, force testing of the complete assembly at full extension has verified design efficacy for the anticipated loading condition (refer to p. 39 for original estimation). Future work is necessary to further validate the design from the perspective of a disabled wheelchair user, likely employing extensive user studies (summarized in Table 14, p. 57). To assist a potential future validation effort, a preliminary validation plan has been developed (Appendix V).

Crucially, the current presenter design exhibits binding of both the drag chain and the seat belt during extension and securement, respectively. The drag chain binding is believed to be a coupled result of an exponential decay of the pushing force between adjacent blocks (Figure 52, p. 61) and instances during extension wherein blocks are loaded in a self-jamming geometry (Figure 53, p. 63). Though both of these phenomena are fundamentally a consequence of internal friction, it is believed that reductions in internal friction alone will not remedy the issue. Rather, these phenomena appear to be inherent flaws of a centrally driven design. The seat belt binding has also been shown to occur for steep pull-angles of the belt, as required for securement from a wheelchair seated position (Figure 54, p. 64). To resolve these two binding issues, prospective solutions have been thoroughly described (p. 69); namely, it is believed that a mouth-driven configuration (Figure 55, p. 69) and a pivoting end plate (Figure 56, p. 70) are promising design iterations that might limit binding if given further exploration.

Finally, the realized challenges through the course of this project have been described, and outstanding risks for eventual use of the prototype design have been enumerated (p. 64). A post-mortem reflection on the broader social context, ethical landscape, and role of influence and inclusion has also been discussed. In general, we believe that the design developed in this work has true potential to promote greater accessibility for an often marginalized community, and hope that future work is sought to further develop, iterate, and validate this unique idea.

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First and foremost, we would like to extend our most sincere gratitude to Dr. Jon Luntz (University of Michigan) and Dr. Paul Alexander (General Motors) for their dedicated help and support throughout the course of this project. Their enthusiasm for engineering and education has been inspirational, and their expertise has been central in promoting the quality of this work. We could not have imagined having better mentors.

We would also like to thank others from General Motors who lent us their time and valuable insight; namely, Mrs. MaryAnn Beebe, Mr. John Katona, and the GM Able resource group at large. These individuals were crucial in helping us define the scope of the problem considered in this work, and guided the development of a solution that is better suited for the target user.

Finally, we would like to thank the University of Michigan Transportation Research Institute (UMTRI) for their support during the span of the project, especially Dr. Kathy Klinich. Dr. Klinich was a significant voice and resource in our project, and was essential to the success of the design.

REFERENCES

[1] A. M. Koontz, D. Ding, Y.-K. Jan, S. de Groot, and A. Hansen, "Wheeled Mobility," *BioMed Res. Int.*, vol. 2015, p. 138176, 2015, doi: 10.1155/2015/138176.

[2] "SEC Seat Belt Presenter problems! | Mercedes-Benz Forum." Accessed: Sep. 24, 2023. [Online]. Available: https://www.benzworld.org/threads/sec-seatbelt-presenter-problems.1455057/

[3] CDC, "Disability Impacts All of Us Infographic | CDC," Centers for Disease Control and Prevention. Accessed: Sep. 22, 2023. [Online]. Available: https://www.cdc.gov/ncbddd/disabilityandhealth/infographic-disability-impacts-all.html

[4] L. Kraus, E. Lauer, R. Coleman, and A. Houtenville, "2017 Disability Statistics Annual Report," Disability Compendium. [Online]. Available: https://disabilitycompendium.org/sites/default/files/user-uploads/2017_AnnualReport_2017_FINAL.pdf

[5] S. Brumbaugh, "Travel Patterns of American Adults with Disabilities," Bureau of Transportation Statistics. Accessed: Sep. 22, 2023. [Online]. Available: https://www.bts.gov/travel-patterns-with-disabilities

[6] J. Wallgren, "How Does Infrastructure Limit The Mobility Of Disabled People - The Last Tackle." Accessed: Sep. 22, 2023. [Online]. Available: https://www.thelasttackle.com/the-mobility-of-disabled-people/

[7] R. A. Cooper, R. Cooper, and M. L. Boninger, "Trends and issues in wheelchair technologies," *Assist. Technol. Off. J. RESNA*, vol. 20, no. 2, pp. 61–72, 2008, doi: 10.1080/10400435.2008.10131933.

[8] "Emerging Trends in Disability," PRB. Accessed: Sep. 22, 2023. [Online]. Available: https://www.prb.org/resources/emerging-trends-in-disability/

[9] Institute of Medicine (US) Committee on Disability in America, *The Future of Disability in America*. in The National Academies Collection: Reports funded by National Institutes of Health. Washington (DC): National Academies Press (US), 2007. Accessed: Sep. 22, 2023. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK11434/

[10] "Persons with a Disability: Labor Force Characteristics - 2022," Bureau of Labor Statistics, USDL-23-0351, Feb. 2023. [Online]. Available: https://www.bls.gov/news.release/pdf/disabl.pdf

[11] R. Vallas, K. Knackstedt, and V. Thompson, "7 Facts About the Economic Crisis Facing People with Disabilities in the United States," The Century Foundation. Accessed: Sep. 22, 2023. [Online]. Available: https://tcf.org/content/commentary/7-facts-about-the-economic-crisis-facing-people-with-disabilities-in-the-united-states/

[12] K. Brannigan, "Economic Impacts of Removing Transportation Barriers to Employment for Individuals with Disabilities Through Autonomous Vehicle Adoption," National Disability Institute. Accessed: Sep. 22, 2023. [Online]. Available: https://www.nationaldisabilityinstitute.org/reports/autonomous-vehicle-adoption/

[13] "Equity in Transportation for People with Disabilities." AAPD. [Online]. Available: http://www.civilrightsdocs.info/pdf/transportation/transportation-and-disabilities-v%205-2.pdf

[14] J. Joyner, "Barriers to Independent Living: Public Transportation." Accessed: Sep. 23, 2023. [Online]. Available: https://www.accessibility.com/blog/barriers-to-independent-living-public-transportation

[15] "Trade or Convert Your Car to a Wheelchair Vehicle," BraunAbility. Accessed: Sep. 23, 2023. [Online]. Available: https://www.braunability.com/us/en/blog/mobility-solutions/trade-or-convert-wheelchair-vehicle.html
[16] M. Gebreselassie, "Wheelchair Users' Perspective on Transportation Service Hailed Through Uber and Lyft Apps," *Transp. Res. Rec.*, vol. 2677, no. 5, pp. 1164–1177, May 2023, doi: 10.1177/03611981221140369.
[17] M.-E. McCavert, "The Challenges of Hailing a Taxi as a Wheelchair User," The Mighty. Accessed: Sep. 23, 2023. [Online]. Available: https://themighty.com/topic/disability/hailing-taxi-wheelchair-user/
[18] D. Sauerburger, E. Siffermann, and S. Rosen, "Principles for Providing Orientation and Mobility to People with Vision Impairment and Multiple Disabilities," *Vis. Rehabil. Int.*, vol. 1, no. 1, pp. 52–56, Dec. 2007, doi: 10.21307/ijom-2008-006.
[19] O. Fiol and S. Weng, "Shared Autonomous Vehicles Could Improve Transit Access for People with Disabilities If Regulated Appropriately | Urban Institute," Urban Institute. Accessed: Sep. 22, 2023. [Online]. Available: https://www.urban.org/urban-wire/shared-autonomous-vehicles-could-improve-transit-access-people-disabilities-if-regulated
[20] K. D. Klinich, M. A. Manary, K. J. Boyle, N. R. Orton, J. Hu, and University of Michigan. Transportation Research Institute, "Development of an Automated Wheelchair Tiedown Restraint System," DOT HS 813 275, Oct. 2022. Accessed: Sep. 23, 2023. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/64468
[21] "Safety System and Usability Issues for Wheelchair-Seated Drivers and Passengers of Private Vehicles," RESNA. Accessed: Sep. 23, 2023. [Online]. Available: https://www.resna.org/sites/default/files/legacy/conference/proceedings/2008/Wheeled%20Mobility/vanRoosmalen.html
[22] K. D. Klinich, M. A. Manary, N. R. Orton, K. J. Boyle, and J. Hu, "A Literature Review of Wheelchair Transportation Safety Relevant to Automated Vehicles," *Int. J. Environ. Res. Public. Health*, vol. 19, no. 3, p. 1633, Jan. 2022, doi: 10.3390/ijerph19031633.
[23] K. Frost, G. Bertocci, and Z. Salipur, "Wheelchair Securement and Occupant Restraint System (WTORS) Practices in Public Transit Buses," *Assist. Technol. Off. J. RESNA*, vol. 25, pp. 16–23, Mar. 2013, doi: 10.1080/10400435.2012.680660.
[24] S. J. Bulstrode, A. K. Clarke, and R. A. Harrison, "A critical evaluation of car seat belts for disabled people: the problems of upper limb mobility and manual dexterity," *Int. J. Rehabil. Res. Int. Z. Rehabil. Rev. Int. Rech. Readaptation*, vol. 10, no. 4 Suppl 5, pp. 61–62, 1987.
[25] M. P. Reed and L. van Roosmalen, "A pilot study of a method for assessing the reach capability of wheelchair users for safety belt design," *Appl. Ergon.*, vol. 36, no. 5, pp. 523–528, Sep. 2005, doi: 10.1016/j.apergo.2005.04.002.
[26] P. Alexander, "ME 450 Stakeholder Interview: Dr. Paul Alexander 9/26," Sep. 26, 2023.
[27] J. Katona, "ME 450 Stakeholder Interview: John Katona," Sep. 19, 2023.
[28] K. Klinich, "ME 450 Stakeholder Interview: Dr. Kathleen Klinich," Sep. 18, 2023.
[29] "Q'STRAINT Wheelchair Securement Systems - Making Safety Accessible," Q'STRAINT. Accessed: Sep. 27, 2023. [Online]. Available: https://www.qstraint.com/
[30] "Sure-Lok: Safe & Secure Wheelchair Securement," Sure-Lok. Accessed: Sep. 27, 2023. [Online]. Available: https://sure-lok.com/
[31] K. Frost, G. Bertocci, and C. Smalley, "Wheelchair tiedown and occupant restraint practices

in paratransit vehicles," *PLoS ONE*, vol. 13, no. 1, p. e0186829, Jan. 2018, doi: 10.1371/journal.pone.0186829.
[32] L. W. Schneider *et al.*, "Wheelchair occupant studies," University of Michigan, Ann Arbor, Transportation Research Institute, Technical Report, Jul. 2016. Accessed: Sep. 24, 2023. [Online]. Available: http://deepblue.lib.umich.edu/handle/2027.42/122860
[33] E. S. Chaves, R. A. Cooper, D. M. Collins, A. Karmarkar, and R. Cooper, "Review of the use of physical restraints and lap belts with wheelchair users," *Assist. Technol. Off. J. RESNA*, vol. 19, no. 2, pp. 94–107, 2007, doi: 10.1080/10400435.2007.10131868.
[34] "TITAN 800: 4-Point Wheelchair Securement System." Sure-Lok. [Online]. Available: http://sure-lok.com/wp-content/uploads/pdf_downloads/Titan_800_Inst_Placard.pdf
[35] "Patient Aid Padded Wheelchair Seat Belt." Accessed: Sep. 24, 2023. [Online]. Available: https://www.amazon.com/Patient-Aid-Padded-Wheelchair-Seat/dp/B07FSJN668
[36] "Seat Belt Presenter," MBWorld.org Forums. Accessed: Sep. 24, 2023. [Online]. Available: https://mbworld.org/forums/c63-c63s-amg/637725-seat-belt-presenter.html
[37] "Seat Buckle Assist Device - The JIMMY," Mobility Innovations. Accessed: Sep. 24, 2023. [Online]. Available: https://www.mobilityinnovations.com/the-jimmy/
[38] "Seat Belt Grabber Handle (2-Pack)," Seat Belt Extender Pros. Accessed: Sep. 24, 2023. [Online]. Available: https://www.seatbeltextenderpros.com/seat-belt-grabber-handle-2-pack/
[39] "Seat Belt Grabber Handle - Reviews." Accessed: Sep. 24, 2023. [Online]. Available: https://www.amazon.com/Seat-Belt-Grabber-Handle-buckle/dp/B003AU1BP0#customerReviews
[40] D. Wynn and J. Clarkson, *Design Process Improvement*, 1st ed., vol. 1, 1 vols. Springer London, 2005.
[41] H. Cooper, "ME Capstone Design Process Framework," Fall 2020.
[42] "Design Control Guidance for Medical Device Manufacturers."
[43] R. Loweth, S. Skerlos, H. Cooper, K. Dugan, S. Daly, and K. Sienko, "ME 450 Social Context Block," Social Context Assessment Block. Accessed: Sep. 26, 2023. [Online]. Available: https://umich.instructure.com/courses/641638/pages/social-context-assessment-overview?module_item_id=3175621
[44] S. Hoffman *et al.*, "ME 450 Inclusivity Block," Inclusivity Assessment Block. Accessed: Sep. 26, 2023. [Online]. Available: https://umich.instructure.com/courses/641638/pages/engineering-inclusivity-overview?module_item_id=3175653
[45] General Motors, "Our Path to Zero Barriers," Diversity: Our path to zero barriers. Accessed: Sep. 26, 2023. [Online]. Available: https://www.gm.com/stories/zero-barriers
[46] R. Bellan, "TechCrunch Article," Cruise nears approval to mass-produce robotaxis with no steering wheel, pedals. Accessed: Sep. 26, 2023. [Online]. Available: https://techcrunch.com/2023/09/07/cruise-nears-approval-to-mass-produce-robotaxis-with-no-steering-wheel-pedals/#:~:text=%E2%80%9CAn%20average%20car%20has%20maybe,a%20key%20unlock%20for%20profitability.%E2%80%9D
[47] Progressive, "How many miles does a car last?," How many miles does a car last? Accessed: Sep. 27, 2023. [Online]. Available: https://www.progressive.com/answers/how-many-miles-does-a-car-last/
[48] "FMVSS 209." Dec. 07, 2007.

[49] "RESNA WC-4." ANSI, 2017.
[50] "ADA 4.2." 2010. Accessed: Sep. 25, 2023. [Online]. Available: https://www.ada-compliance.com/space-allowance-reach-ranges
[51] "W3C SC 1.4.3." 2023. Accessed: Sep. 25, 2023. [Online]. Available: https://www.w3.org/
[52] "Visual Acuity," American Academy of Ophthalmology. Accessed: Sep. 25, 2023. [Online]. Available: https://www.aao.org/education/bcscsnippetdetail.aspx?id=3550b1ca-1740-4e7f-8712-70905c99eb26
[53] P. Alexander, "ME 450 Stakeholder Interview: Dr. Paul Alexander," Sep. 12, 2023.
[54] M. A. Beebe, "ME 450 Stakeholder Interview: Mary Anne Beebe," Sep. 20, 2023.
[55] "Gendron Regency 450 Bariatric Wheelchair 450 lbs - American Quality." Accessed: Sep. 25, 2023. [Online]. Available: https://americanqualityhealthproducts.com/heavy-duty-wheelchairs/5288-gendron-regency-450-bariatric-wheelchair-450-lbs.html?utm_campaign=SOPrimary2020&content=662570841761&keyword=&gclid=CjwKCAjw38SoBhB6EiwA8EQVLgyW3ZcuRhiXZMbkn3zQafuDihlU1tyZr6uufboQwtUo6LUPX-_AchoCY_8QAvD_BwE#/seat_width_depth-24_x_20
[56] J. Luntz, "ME 450: Concept Generation," Sep. 26, 2023.
[57] "Occupant Protection," Traffic Safety. Accessed: Oct. 16, 2023. [Online]. Available: https://www.in.gov/cji/traffic-safety/occupant-protection/
[58] G. Agarwal, N. Kidambi, and R. Lange, "Seat Belts: A Review of Technological Milestones, Regulatory Advancements, and Anticipated Future Trajectories," SAE Technical Paper, Warrendale, PA, SAE Technical Paper 2021-01–5097, Oct. 2021. doi: 10.4271/2021-01-5097.
[59] "Replacement Seat Belts," Seat Belts Plus. Accessed: Oct. 19, 2023. [Online]. Available: https://www.seatbeltsplus.com/
[60] K. Page, "How Do Seat Belts Work? | YourMechanic Advice." Accessed: Oct. 08, 2023. [Online]. Available: https://www.yourmechanic.com/article/how-do-seat-belts-work
[61] "Seat Belt Helper," Virtual Showroom™ (VSR). Accessed: Oct. 09, 2023. [Online]. Available: https://store4881025.ecwid.com/Seat-Belt-Helper-p41316369
[62] "Bioengineers design better seat belts to help people with dexterity challenges buckle up | VCH Research Institute." Accessed: Oct. 19, 2023. [Online]. Available: https://www.vchri.ca/stories/2019/11/03/bioengineers-design-better-seat-belts-help-people-dexterity-challenges-buckle
[63] G. Friebis, "'Click It or Ticket' reminds everyone to wear a seatbelt." Accessed: Oct. 08, 2023. [Online]. Available: https://www.mytwintiers.com/news-cat/click-it-or-ticket-reminds-everyone-to-wear-a-seatbelt/
[64] "Aircraft Seatbelts the world's leader in aviation restraints," Amsafe. Accessed: Oct. 08, 2023. [Online]. Available: https://www.amsafe.com/restraints/aircraft-seatbelts/
[65] "Shop by Seat Belt Buckle | SeatBeltsPlus.com." Accessed: Oct. 08, 2023. [Online]. Available: https://www.seatbeltsplus.com/category/seat-belt-buckle.html
[66] "Wheelchair clipart | Creazilla." Accessed: Oct. 08, 2023. [Online]. Available: https://creazilla.com/nodes/16806-wheelchair-clipart
[67] "Drag Chain Cable Wire Chain." Accessed: Oct. 08, 2023. [Online]. Available: https://www.amazon.com/FYSETC-Plastic-Flexible-Electrical-Machines/dp/B07K59D3DH?th=1

[68] "PKK - Plastic drag chain by EKD Systems GmbH | DirectIndustry." Accessed: Oct. 08, 2023. [Online]. Available: https://www.directindustry.com/prod/ekd-systems-gmbh/product-15339-61600.html
[69] "Cable Drag Chains Guide," Tsubaki Power Transmission. Accessed: Oct. 19, 2023. [Online]. Available: https://www.ustsubaki.com/resources/knowledge-center/cable-drag-chains-guide/
[70] "Zip Chain Actuator®," TSUBAKI POWER TRANSMISSION, LLC. Accessed: Oct. 19, 2023. [Online]. Available: https://www.ustsubaki.com/products/zip-chain-actuator/
[71] "Automatic Seat Belts." Accessed: Oct. 19, 2023. [Online]. Available: https://www.mccarthycollisioncenters.com/blog/what-ever-happened-to-automatic-seat-belts
[72] P. Alexander, "ME 450 Stakeholder Interview: Dr. Paul Alexander 10/5," Oct. 05, 2023.
[73] "Design Thinking Bootleg," Stanford d.school. Accessed: Oct. 19, 2023. [Online]. Available: https://dschool.stanford.edu/resources/design-thinking-bootleg
[74] "Wheelchair, standard model," GrabCad. Accessed: Oct. 09, 2023. [Online]. Available: https://grabcad.com/library/wheelchair-standard-model
[75] "Wheelchair securement systems for vehicles | BraunAbility Europe." Accessed: Oct. 08, 2023. [Online]. Available: https://www.braunability.eu/en/products/tie-downs-and-seatbelts/wtors/
[76] "TechOWL PA (@techowlpa)," TikTok. Accessed: Oct. 19, 2023. [Online]. Available: https://www.tiktok.com/@MS4wLjABAAAAhByA7hiMSAzzVqvpwMOVfBU2KZrm47ANRbzNu8SIVJJLu9c43j9xvUpFCXjfFie0
[77] "What Are Drag Chains & Why Are They Used? - Metreel." Accessed: Oct. 19, 2023. [Online]. Available: https://www.metreel.co.uk/blog/what-are-drag-chains-why-are-they-used/
[78] H. Russell, *Statics and Mechanics of Materials*, 3rd Edition. Pearson, 2010.
[79] "tp-209-08_tag.pdf." Accessed: Oct. 19, 2023. [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/tp-209-08_tag.pdf
[80] lytemar, "Yield Strength of Plastics." Accessed: Oct. 08, 2023. [Online]. Available: https://www.engineeringclicks.com/yield-strength-of-plastics/
[81] L. C. Lundstrom, "The Safety Factor in Automotive Design," SAE Technical Paper, Warrendale, PA, SAE Technical Paper 660539, Feb. 1966. doi: 10.4271/660539.
[82] P. Alexander, "ME 450 Stakeholder Interview: Dr. Paul Alexander 10/24," Oct. 24, 2023.
[83] A. Uchowski and J. Jackowski, "Analysis of Properties of Operation of the Supporting Equipment for the Seat Belts," Nov. 2023.
[84] P. Alexander, "ME 450 Stakeholder Interview: Dr. Paul Alexander 10/31," Oct. 31, 2023.
[85] "Overview of materials for High Density Polyethylene (HDPE), Injection Molded." Accessed: Nov. 20, 2023. [Online]. Available: https://www.matweb.com/search/datasheet_print.aspx?matguid=fce23f90005d4fbe8e12a1bce53ebdc8
[86] D. W. Green, J. E. Winandy, and D. E. Kretschmann, "Mechanical properties of wood," *Wood Handb. Wood Eng. Mater. Madison WI USDA For. Serv. For. Prod. Lab. 1999 Gen. Tech. Rep. FPL GTR-113 Pages 41-445*, vol. 113, 1999, Accessed: Oct. 25, 2023. [Online]. Available: https://www.fs.usda.gov/research/treesearch/7149
[87] "6061 Aluminium Alloy," Ferguson Perforating. Accessed: Nov. 20, 2023. [Online]. Available:

https://www.fergusonperf.com/the-perforating-process/material-information/specialized-aluminum/6061-aluminium-alloy/
[88] "What kind of glue works on HDPE pipes?" Accessed: Nov. 20, 2023. [Online]. Available: https://www.graservices.com/what-kind-of-glue-works-on-hdpe-pipes#
[89] "Original Gorilla Glue," Gorilla Glue. Accessed: Nov. 20, 2023. [Online]. Available: https://www.gorillatough.com/product/original-gorilla-glue/
[90] "All You Need To Know About HDPE Plastic | Adreco Plastics." Accessed: Nov. 20, 2023. [Online]. Available: https://adrecoplastics.co.uk/hdpe-plastic/
[91] "Polycarbonate vs. Acrylic | Acme Plastics." Accessed: Nov. 20, 2023. [Online]. Available: https://www.acmeplastics.com/acrylic-vs-polycarbonate#
[92] "HDPE vs. Polycarbonate: Material Differences and Comparisons." Accessed: Nov. 20, 2023. [Online]. Available: https://www.xometry.com/resources/materials/hdpe-vs-polycarbonate/
[93] FindTape.com, "DAP Weldwood Original Contact Cement @ FindTape," FindTape.com. Accessed: Nov. 20, 2023. [Online]. Available: https://www.findtape.com/DAP-Weldwood-Original-Contact-Cement/p1506/
[94] "Plastic Semi Closed CNC Machine Tool Cable Wire Carrier Drag Chain 1M Black," Amazon. Accessed: Nov. 20, 2023. [Online]. Available: https://www.amazon.com/Plastic-Machine-Carrier-Ted-Lele/dp/B07VXVL9RY/ref=sr_1_6?crid=2AZ14MC4XGTLB&keywords=drag%2Bchain%2B50mm&qid=1700518920&sprefix=drag%2Bchain%2B50mm%2B%2Caps%2C140&sr=8-6&th=1
[95] "Friction - Friction Coefficients and Calculator." Accessed: Nov. 12, 2023. [Online]. Available: https://www.engineeringtoolbox.com/friction-coefficients-d_778.html
[96] "Coefficient of Friction Equation and Table Chart." Accessed: Nov. 20, 2023. [Online]. Available: https://www.engineersedge.com/coeffients_of_friction.htm
[97] "GM Seat Belt - Guaranteed Genuine from GMPartsGiant.com." Accessed: Nov. 21, 2023. [Online]. Available: https://www.gmpartsgiant.com/oem-gm-seat_belt.html
[98] "The capstan equation." Accessed: Dec. 09, 2023. [Online]. Available: https://www.tspi.at/2021/11/15/capstanequation.html
[99] "1.3: The Derivative- Infinitesimal Approach," Mathematics LibreTexts. Accessed: Dec. 09, 2023. [Online]. Available: https://math.libretexts.org/Bookshelves/Calculus/Elementary_Calculus_(Corral)_v2/01%3A_The_Derivative/1.03%3A_The_Derivative-_Infinitesimal_Approach
[100] L. Eitel, "Basics of rigid-chain actuators," Linear Motion Tips. Accessed: Dec. 10, 2023. [Online]. Available: https://www.linearmotiontips.com/basics-rigid-chain-actuators/
[101] "Understanding How Rubber Tracks Are Made." Accessed: Dec. 11, 2023. [Online]. Available: https://www.mclarenindustries.com/us/en/news-and-resources/news/276/understanding-how-rubber-tracks-are-made/
[102] R. Mai, "Process for making rubber tracks and rubber track made thereby," EP0419424B1, Oct. 12, 1994 Accessed: Dec. 11, 2023. [Online]. Available: https://patents.google.com/patent/EP0419424B1/en#
[103] "ABS Filament l 3D Printer Filament l 3D Materials l COEX LLC." Accessed: Nov. 21, 2023. [Online]. Available: https://coex3d.com/pages/about-abs-filament#
[104] J. Rubin, D. Chisnell, and J. Spool, *Handbook of Usability Testing: How to Plan, Design, and Conduct Effective Tests*, 2nd ed. John Wiley & Sons, Incorporated, 2008.

APPENDIX I

Bill of Materials

Table 15: Comprehensive bill of materials for fabrication of prototype drag chain presenter considered in this work.

Subsystem	Part Description	Source	Unit Price	Quantity	Total Cost
Drag chain	2" x 1" aluminum tubing (per 1 ft)	Online Metals	$3.94	6	$23.64
	Seat belt webbing (per 1 ft)	Amazon	$0.47	5	$2.35
	1/8" elastic cord (per 1 ft)	Amazon	$0.25	10	$2.50
	1/8" x 1/4" aluminum rivet (per 100)	Home Depot	$7.87	2	$15.74
	1/8" ID aluminum washer (per 10)	Home Depot	$1.13	16	$18.08
	Presenter end plate (ABS filament)	Fabricated, ABS	$24.99	0.08	$2.00
Support channel	3" x 2" aluminum tubing (per 1 ft)	Metals Depot	$13.72	1	$13.72
	1/2" HDPE sheet (8" x 8")	Amazon	$19.99	1	$19.99
	JB weld adhesive	Home Depot	$8.68	1	$8.68
	#8 wood screws (1/2" length, per 8)	Home Depot	$1.38	2	$2.76
Housing + spool	Drag chain housing (ABS filament)	Fabricated, ABS	$24.99	2	$49.98
	Spool (ABS filament)	Fabricated, ABS	$24.99	0.2	$5.00
	Retractor and latch plates	Sponsor provided	$0.00	1	$0.00
	M5 x 8mm heat set knurled nut (per 10)	Amazon	$1.15	1	$1.15
	M4 x 80 hex socket head cap bolt	Amazon	$0.34	8	$2.72
	M4 x 100 hex socket head cap bolt	Amazon	$0.35	2	$0.70
	M4 nylon insert lock nut	Amazon	$0.07	10	$0.70
	30mm ID deep groove ball bearing	Amazon	$4.00	2	$8.00
	0.050" clear acrylic sheet	Scrap material	$0.00	1	$0.00
Motor + electronics	Automotive power window motor	Amazon	$28.99	1	$28.99
	M5 x 20mm socket head cap screw	Amazon	$0.20	3	$0.60
	Arduino nano microcontroller	Amazon	$12.99	1	$12.99
	Arduino nano terminal adapter board	Amazon	$2.93	1	$2.93
	Variable DC power supply	Amazon	$18.99	1	$18.99
	12V SPDT relay module	Amazon	$3.70	3	$11.10
	5V DC to DC converter	Amazon	$7.99	1	$7.99
	Momentary push button switch	Amazon	$4.50	2	$9.00
	3-pin SPDT micro limit switch (per 25)	Amazon	$6.99	1	$6.99
	10 kΩ resistor (per 100)	Amazon	$5.99	1	$5.99
	24 AWG silicon wire (per 20 ft)	Amazon	$6.28	1	$6.28
	6-pin connector (male+female sockets)	Amazon	$7.99	1	$7.99
Test Rig	6 ft 2x4" pine lumber	Scrap material	$0.00	4	$0.00
	Plywood for base	Scrap material	$0.00	1	$0.00
	Seat belt buckle receptacles	Sponsor provided	$0.00	2	$0.00
				Total	**$297.55**

APPENDIX II

Manufacturing and Assembly Plan

The final presenter design consists of three main subassemblies: 1) the drag chain, 2) the support channel, and 3) the housing with supporting plastic components. Each of these subsystems have tolerances and manufacturing requirements that will be discussed separately as follows.

Drag Chain. To construct the drag chain, 38 individual chain block elements must be fabricated. The individual chain blocks are made from 2" x 1" (50.8 x 25.4 mm) 6061 T6 aluminum rectangular tubing with 1/8" (3.175 mm) wall thickness, and are cut to a length of 1.5" (38.1 mm). Notably, tight tolerance must be maintained between blocks in terms of width and thickness (determined by quality of stock material), but there is low tolerance demand on the length of each individual block. Consequently, a horizontal bandsaw provides appropriate tolerance and speed for creating the necessary number of blocks. Each cut face is then filed to deburr rough edges. Then, four 1/8" (3.175 mm) holes are drilled through the major faces of each individual block. Figure 58 provides the relevant block dimensions.

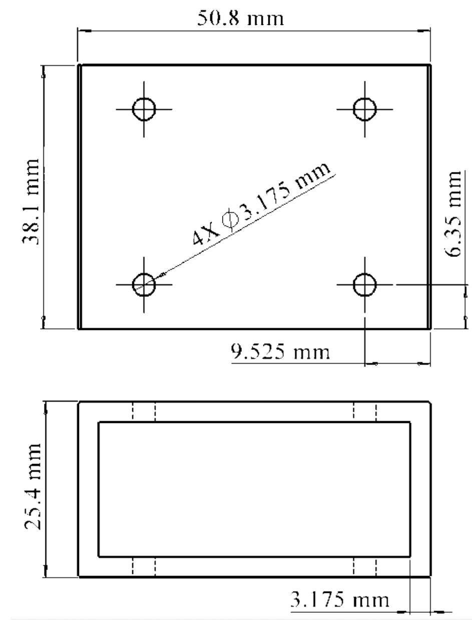

Figure 58: Dimensions of chain blocks.

Notably, the rivets used to secure the webbing backing and the elastic cable use require the same relative positioning and sizing of holes, meaning that the eight 1/8" (3.175 mm) holes required for each block can be accomplished in four drilling operations. Similarly to the block length, the dimensional accuracy of these holes is not of high priority; the rivet location through the webbing can be adjusted or the elastic can stretch accordingly. Thus, a drill press is of appropriate speed and accuracy to fabricate these holes. The position of the holes are practically located on the blocks by scribing the aluminum face with a pair of calipers, and center punching the appropriate locations to limit drill bit wandering. After each hole is drilled, a deburring bit is used with a handheld drill to chamfer the rough cuts. This step is important for subsequent routing of the elastic cable. With the blocks fabricated, the webbing is then installed by carefully routing each rivet and washer through the webbing material (avoiding nicking or cutting the fabric strands) and securing into the relevant block holes using a handheld rivet gun (as depicted in Figure 59).

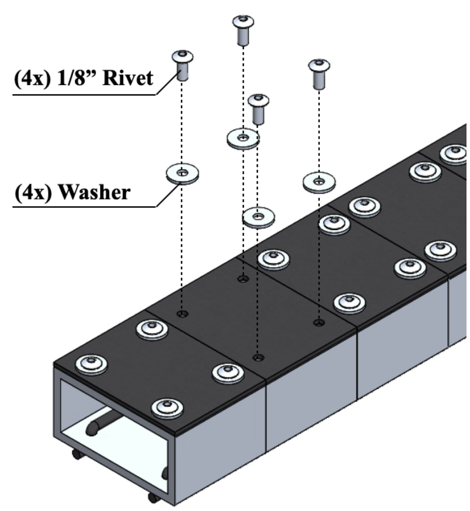

Figure 59: Chain construction with rivets.

Finally, the elastic cable is routed by hand through the holes on the bottom of the chain, and pretensioned appropriately. In practice, because the minimum necessary pretensioning was determined to be very low (refer to Elastic Pretensioning Calculations, p. 45), this tension was set rather informally by hand.

Support Channel. The structural casing of the support channel is constructed of 3” x 2” (76.2 x 50.8 mm) 6061 T6 aluminum rectangular tubing with 1/8” (3.175 mm) wall thickness. Similar to the individual block segments, this is cut to a length of 7.5” (190.5 mm) using the horizontal bandsaw because there is low dimensional demand on channel length. Inside the aluminum channel, four individual HDPE guide rails are fabricated to minimize internal friction and aid chain alignment. Because these guides serve as the load bearing surface for the chain during operation, there is a high tolerance demand to avoid slop in the chain kinetics. Thus, these channels are milled to appropriate thickness to ensure an appropriately tight fit. These HDPE guides are then secured into the aluminum casing with pre-drilled holes and #8 wood screws to enable maintenance (in case they are deemed a consumable component from wear over time). Figure 60 presents this construction of the support channel assembly.

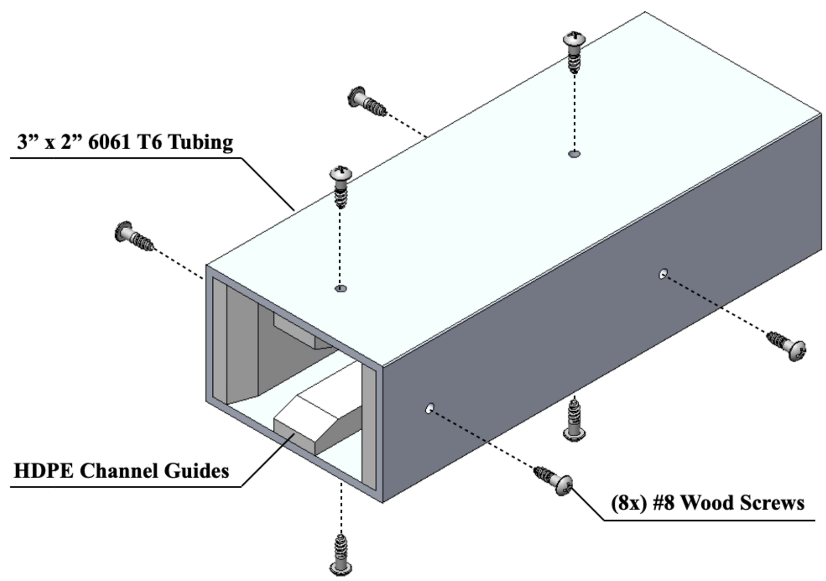

Figure 60: Exploded view of support channel with component callouts.

Housing, Spool, Presenter End Plate, and Electronics Box. Due to geometric complexity and comparatively low structural demand, the housing, spool, and presenter end plate are 3D printed using a traditional FDM machine. ABS filament material was selected for its relatively high strength and ease of printing [103]. More specifically, these components are created with 20 mm layer height, 70% infill, and 100 mm/s nozzle speed to balance strength, material usage, and print speed. Support is used to aid construction of overhanging features. To ensure proper bed adhesion and minimal warpage of the larger components (such as the two halves of the housing), a heated bed plate set to 65ºC is used with large rafts. Following printing, all supporting material is removed and the part is sanded and cleaned.

Final Assembly. To assemble the full presenter system, the housing assembly is first constructed. Namely, the spool and bearings are nested in the two housing halves, which are mated together using long M4 bolts through the relevant 3D printed holes. A thin (0.050" or 1.27 mm) acrylic sheet is secured on the inside of the housing faceplate using double sided tape to prevent the drag chain from catching on the openings in the faceplate. At this point, the drag chain is attached to the mating feature on the chain spool using small wood screws. An exploded view of this assembly with callouts for the major components is provided in Figure 61. Note that the drag chain is not pictured so as to aid visualization of the other components.

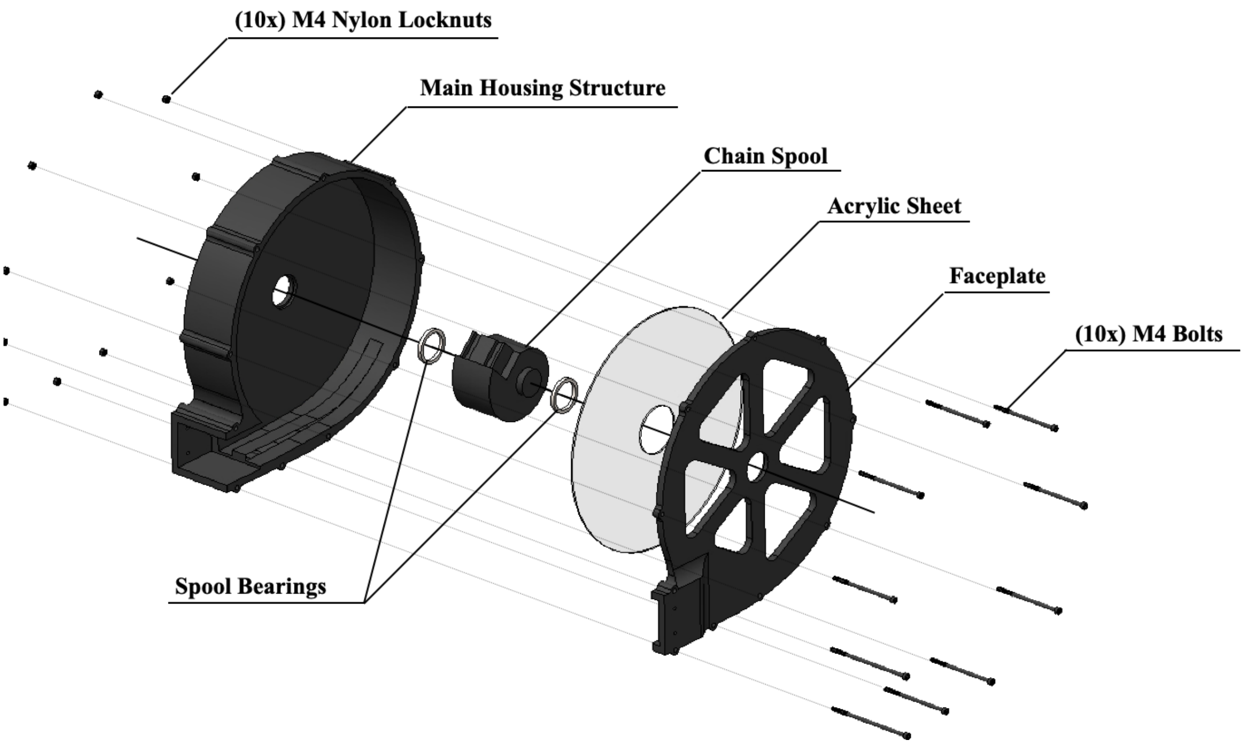

Figure 61: Exploded view of presenter housing assembly with callouts for relevant components.

Once the housing is assembled with the nested spool and drag chain, the support channel is then attached using #8 wood screws (similar to those used prior for fastening the HDPE guides to the channel itself). Pre-drilled holes are made both in the housing and channel to prevent cracking of the 3D print and ease assembly. Figure 62 depicts this assembly step.

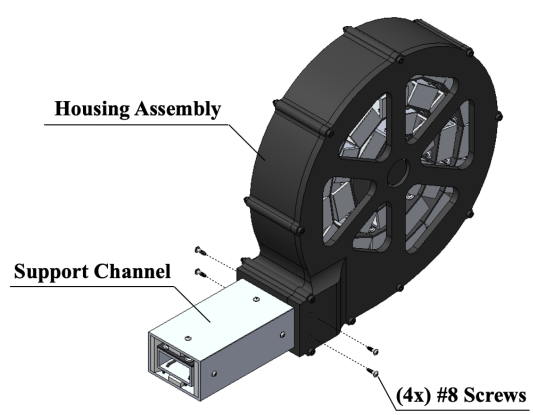

Figure 62: Mating of support channel and housing.

Finally, the presenter end plate and the OEM belt retractor can be attached to the drag chain and support channel, respectively. Similar to the drive spool, the presenter end plate is attached to the drag chain using small wood screws. Because of the demonstrative nature of this prototype presenter, the OEM belt retractor was temporarily fixed in place using double sided tape. This is meant to aid future integration with the retractor and mounting fixture in the Cruise Origin platform (yet to be fully resolved at the time of this work) by simply removing the temporary demo retractor. Of course, this securement method is wholly insufficient to account for the retractor loads experienced in a crash scenario, but was deemed appropriate for the functional scope of this prototype. Figure 63 depicts this addition of the presenter end plate and belt retractor.

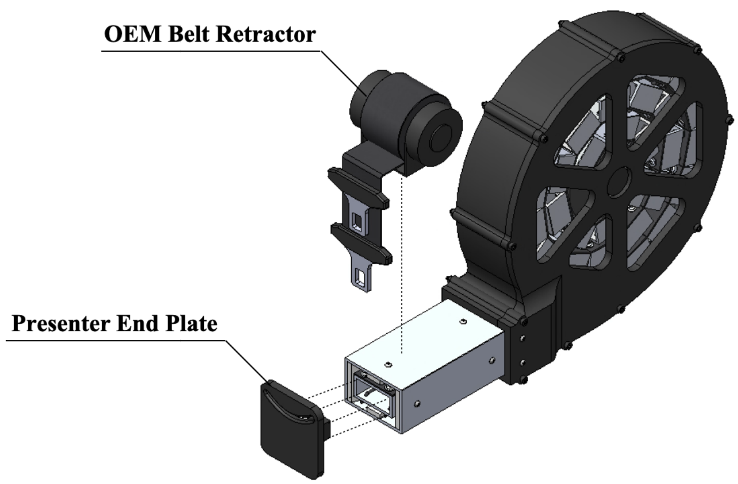

Figure 63: Addition of presenter end plate and belt retractor.

The final assembly step involves installing three M5 heat set inserts into the mounting points for the motor, as depicted in Figure 64. Notably, the associated control electronics (previously described in Supporting Electronics, p. 48) were designed to simply provide demonstrational support for the presenter system, and thus are not included in this manufacturing plan. In potential future deployment of this system into the Cruise Origin platform, these controls would be better integrated into the vehicle to improve the user experience, and thus are of secondary importance in the context of this work.

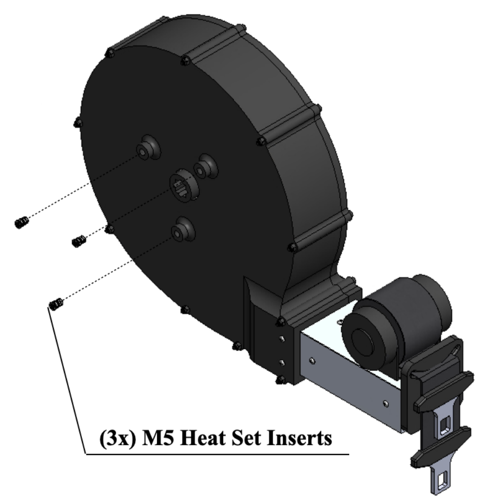

Figure 64: Installation of heat set inserts.

Following installation of the motor and supporting electronics, the presenter assembly is complete.

APPENDIX III

GM Able Validation Survey

The following survey was distributed to the GM Able resource group to attempt to begin preliminary validation of the prototype presenter design:

Hello! This survey is to help with the validation of our ME450 project at the University of Michigan. We presented to the GM Able group on Monday, December 4th, and wanted to reach out to get any more feedback, and work on our validation efforts for our final design report.
We have attached a few images in the document (linked below) to give you an idea of how the system works, if you were not able to attend the presentation.

1. Were you able to attend the presentation on December 4th?
2. Please see Figure 2 in the Supporting Documentation of the CAD and the wood prototype. On a scale from 1 to 5, how socially inert is the presenter? We define socially inert as not flagging the user to be in need of an accessibility device. Please consider that the final system will likely not be made of wood.

    1: Very socially inert to 5: Not socially inert at all.

3. Does the system seem fairly intuitive?
4. Is there anything that we can do to make the system more intuitive?
5. Does it seem like the system can be used independently by the wheelchair user? (i.e. suitable for an autonomous vehicle where the user will likely be alone?) Please see Figure 3 in the Supporting Documentation
6. Is there anything that we can do to make the system more independent? (i.e. more single wheelchair user "friendly")
7. Does it seem reasonably easy to buckle and unbuckle? Please see Figure 3 in the Supporting Documentation.
8. Is there anything that we can do to make the system easier to buckle or unbuckle?
9. Do you see any potential pain or frustration points with the system? If so, please list/explain them here.
10. Any additional comments, concerns, feedback:

APPENDIX IV

Expert Evaluation
Dr. Klinich, UMTRI (responses in red)
On 12/9/2023 1:35 PM, Gabrielle Tibbenham wrote:
Hello Dr. Klinich,

We were so happy to see you at the Design Expo last week! I wanted to reach out to get any preliminary feedback you may have for our design that we could include in our final report. If you could answer a few of the questions I have below, that would be great!

1. On a scale from 1 to 5, how socially inert is the presenter? We define socially inert as not flagging the user to be in need of an accessibility device.
3, but it depends. Would it be available at every location? Then more so. But if only at a wheelchair station, that kind of makes it not socially inert.

2. Does the system seem fairly intuitive? Is there anything we can do to make it more intuitive?
I thought so. Assuming there would be an instructional video on an AV for docking and other steps where using the seatbelt assist could be included.

3. Does it seem like the system could be used independently by a wheelchair user? Is there anything we can use to make it more independent?
As I mentioned before, your project addresses an extremely challenging issue. I am guessing that some people who can't reach the shoulder belt in a typical situation may lack the dexterity to route and buckle as well. Most of the participants we've had over the last few years were able to come independently to UMTRI to be in our study, partly because it was a requirement that they had to be able to transfer to our study wheelchairs. One volunteer came with a care partner, and he wasn't able to push a button to activate our belt donning system, which led us to change the design so it had raised buttons that could be operated with a fist.

4. Does it seem easy to buckle and unbuckle? Is there anything we can do to make it easier?
Relative to the first point, some way to be able to operate with fist rather than fingers for someone with limited dexterity.

5. Did you see any potential pain or frustration points with the system?

Lastly, if you have any additional comments, concerns, or feedback, please let me know!
I thought the mechanism was cool and am impressed at your solution for a really difficult problem!
--
Kathleen D. Klinich, PhD (she/her/hers) Research Scientist, DEI Lead University of Michigan Transportation Research Institute, 2901 Baxter Rd. Ann Arbor MI, 48109 (734) 936-1113
https://namedrop.io/kathleenklinich

APPENDIX V

Validation Plan - Developed from the Handbook of Usability Testing [104]

1. Research questions:
    - How easy is the system to use for a wheelchair user?
    - How quickly does the user learn and use the system as a whole?
    - What obstacles prevent the user from using the system effectively?
2. Hypothesis: The user shall be able to operate the system to the extension necessary for their specific case, and then reach, pull, route, and buckle themselves into the vehicle in less than 1 minute.
3. Summarize Participant characteristics:
    - Name
    - Age
    - Occupation
    - Disability
    - History of disability
4. Give basic instructions of how system works
    - Buttons for extension and retraction
5. Complete full use case of system- begin timer
    - "Dock" wheelchair
    - Press button to extend
    - Reach, grasp, route, buckle
    - Press button to retract
    - Wait as if a distance has been covered
    - Press button to extend
    - Unbuckle, un-route, place in original position
    - Press button to retract
6. Interview user
    - What did you think?
    - What did you like about the experience?
    - What did you not like about the experience?
        - Any pain points?
        - Did you feel particularly frustrated with the system at any point? If so, when?
    - Likert Scale rankings
    - Ask about things observers noticed- "I noticed that you had trouble during XX, could you tell me what you were thinking then?"
    - Allow for open discussion
7. Compile and apply any changes that need to be made

TEAM MEMBER BIOS

John Abernethy

John is majoring in mechanical engineering with a minor in electrical engineering and overall a concentration in controls and robotics. He is from South Lyon, MI which is only about 30 minutes away from Ann Arbor. John always had an interest in the automotive field ever since he was little. Both his grandfather and father worked their whole lives in the automotive industry.

In recent years, John had three internships at two companies: Lear Corporation and General Motors. Each experience contributed a different way to John's learning which has helped him become an even better engineer. After graduating from the University of Michigan, John is excited to start his full time job at General Motors.

Outside of work and school, John loves to swim, golf, and relax with his family. Growing up in Southeast Michigan, John loves watching all Detroit sports throughout the year.

Michael Michaud

Michael is majoring in mechanical engineering with a concentration in design. He is originally from Plymouth, MI but now calls Ann Arbor home. He developed a passion for engineering as a child learning in his grandfather's machine shop in Franklin, TN.

For the past two years, Michael has worked at Yazaki NA, first as an intern and Co-op in low voltage connector design, and more recently as an associate design engineer in high voltage couplers and connectors. After graduation, Michael is interested in working with an innovative and engaging engineering company.

In his free time, Michael enjoys spending time outdoors backpacking and rock climbing. Also, learning how to fix anything and everything is a passion of his.

Gabi Tibbenham

Gabi is majoring in mechanical engineering with an international minor. She is from West Bloomfield, MI, but now calls Armada, MI home. Gabi began to be interested in mechanical engineering at the young age of 3, when she was given a children's plastic tool set, to be just like her engineer parents. She participated in her high school's robotics team, and this gave her an interest in the design process, manufacturing/fabrication, and problem solving.

Gabi's industry experiences include two internships at FANUC America Corporation in the Automotive Segment, as well as on the Human Powered Submarine Student Project Team. After her graduation in December, she plans to work in Virginia Beach, VA for NAVSEA as a test engineer.

In her free time, Gabi loves to tap dance, SCUBA dive, go off-roading, and spend time with her family. She loves the Great Lakes, and being on the water is one of her favorite pastimes.

Jack Zboril

Majoring in mechanical engineering with a minor in business, Jack is a passionate Wolverine originally from Orlando, Florida. His interest in mechanical engineering started at a young age; he often tinkered on cars with his ex-mechanic father in their garage. While working on these projects, he became interested in how the parts and systems he was interacting with were ultimately designed.

Through the course of his early career, Jack has worked in a variety of industries from automotive to theme park ride design. In his most recent role at Roush, he worked as an engineering consultant for interesting projects such as an electric VTOL platform and a gyroscope for passenger yachts. After graduating in December, Jack plans to move to Seattle to pursue a full time job as a test development engineer on SpaceX's Starlink program.

Personally, Jack loves mountain biking and skiing, spending a lot of time doing both in Park City, Utah. He runs a small eBay business refurbishing and reselling skis, and is currently working on building a custom mountain bike.