Design of Reconfigurable Interior for Autonomous Vehicle Prototype

Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

by

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Abstract

Alternative Perspective for User Experience 1 (APEX 01) is a two-year collaborative design project sponsored by Honda Research Americas. Honda asked university students from The Ohio State University and ArtCenter College of Design to develop and demonstrate the user experience of a 2030 Autonomous, Electric, Connected vehicle. The interdisciplinary student team conducted trend research, future forecasting, defined user experience scenarios, and developed a concept interior capable of enabling the desired user experiences. Following concept generation, a full-scale interior mockup was designed and constructed in order to demonstrate the user experience.

One element of the APEX 01 user experience is a reconfigurable interior. This paper will discuss the design of the reconfigurable vehicle interior mockup. The reconfigurable interior is capable of shifting between several usage modes, including a novel seating configuration mimicking a living room. To enable the various usage modes, a folding steering wheel, collapsible pedal, lifting roof, and moving seating were developed. These mechanized items were integrated with the aesthetic design of the vehicle interior. User experience scenarios were choreographed in order to determine the necessary speed for each mechanism. Software was developed to control the position of the various elements.

The interior mockup was assembled and the motion of the elements validated. On May 15th, 2018 APEX 01 was presented to Honda, allowing Honda executives to experience OSU and ArtCenter's vision of future autonomous vehicles.

Dedication

Dedicated to my parents, who from young age encouraged me to experiment, create, and stay curious.

Acknowledgements

I would like to thank Dr. Shawn Midlam-Mohler for his advisory on this project and continued support over the past two years. I would like to thank those at Honda Research Americas for their advice and guidance, and for providing this opportunity to reimagine the future of transportation. Joan Smith and John Barlow have been invaluable in supporting this project within Honda, helping with design critiques, and providing project management advise.

ArtCenter College of Design was also integral to this project, and I would like to thank the student team of designers who led the trend research, future forecasting, and storyboarding during the initial stage of the project. Shinngaram Choi and Saurabh Rathi stayed on this project for additional time as interns and their design sensibilities were critical in the final output of this project. I would like to thank those at CAR for hosting our project, and Jim Shively for his electrical advice and support. Finally, I would like to thank those at Goken America and Jason Robinson from CDME for their design and fabrication support.

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Publications

Y. She, H. J. Su, and C. J. Hurd. Shape Optimization of 2D Compliant Links for Design of Inherently Safe Robots. ASME. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Volume 5B: 39th Mechanisms and Robotics Conference ():V05BT08A004. doi:10.1115/DETC2015-46622.

Y. She, C. J. Hurd and H. J. Su, "A transformable wheel robot with a passive leg," 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, 2015, pp. 4165-4170. doi: 10.1109/IROS.2015.7353966

Fields of Study

Major Field: Mechanical Engineering

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Chapter 1: Introduction

This introduction will provide background on the APEX 01 project and the questions it seeks to answer. The interdisciplinary team involved is also introduced. Finally, the focus of this thesis, within the larger APEX 01 project, is discussed.

1.1 Alternative Perspective for User Experience 01 Project

APEX, or Alternative Perspective for user EXperience, is a process being developed by Honda Research Americas to guide university collaboration. The university collaboration is used for future concept development and technology sensing. Honda has university students design a product, and the student output provides an external perspective on technology, design, and social trends. The APEX process is modeled off of lean startup, making it an efficient way to quickly investigate and prototype ideas. After an APEX project has been completed, the concepts generated are used as starting points for technology sensing within Honda.

APEX 01 is the first Honda-sponsored project to follow the APEX process. The challenge proposed to university students was to design and demonstrate the interior user experience of an Autonomous Connected Electrified (ACE) Level 4 autonomous vehicle. The design targets were broad in order to avoid limiting the student team. The design targets can be seen in Table 1.

Table 1: Design Targets

Model Year	2030
Market	North America
Segment	Entry Luxury
Vehicle	Level 4 Autonomous
Proposed User	Millennial Female, Single, No Kids

In addition to these targets, the student team was told that there were no design constraints relating to passive safety. This was to encourage novel and non-traditional interior layouts. Level 4 autonomy required the non-driving user experience be considered. No constraints were placed on the sales model of the vehicle.

1.2 APEX 01 Project Overview

The APEX 01 student team was split between two universities: The Transportation Design department at ArtCenter College of Design and the College of Engineering at The Ohio State University. The project was broken into six phases. ArtCenter lead the concept development during phase one through three. Technology feasibility consultation was provided by OSU during these phases. OSU lead the full-scale interior mockup design and construction during phases four through six. Aesthetic design support was provided by ArtCenter during phase four in order to help refine the appearance of the full-scale mockup before construction began. Figure 1 shows the dates of each APEX 01 phase.

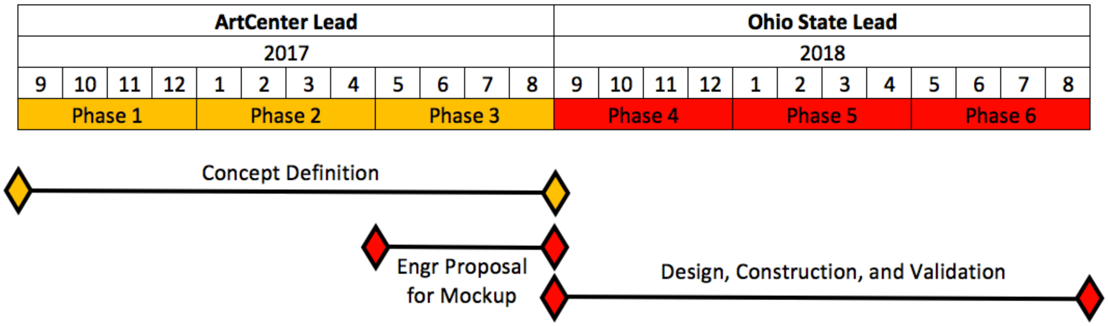


Figure 1: APEX Phases

In addition to the student team, support was provided by Honda suppliers Goken America and 3M, as well as the Center of Design and Manufacturing Excellence (CDME). Goken America provided design support for the roof, interior panels, and rear seat of the interior mockup. 3M provided lighting technology for demonstration in the interior mockup. CDME provided design support for the seat mechanisms as well as construction support.

1.3 Thesis Objective: Reconfigurable Interior

One aspect of the user experience developed during APEX 01 was a reconfigurable interior capable of transforming between different seating configurations and driving modes. The objective of this thesis is to design and construct this full-scale reconfigurable vehicle interior for demonstration. Various elements make up the reconfigurable interior, such as a moving seating, steering wheel, and pedal. Other features of the APEX 01 full-scale mockup will be covered as relevant to the transforming interior.

This thesis is composed of seven chapters. Chapter 1 describes the APEX project and thesis objective. Chapter 2 reviews vehicle autonomy and its impact on interior layouts. Chapter 3 provides background information on the concept development of the interior design and user experience. Chapter 4 covers the engineering project management strategies used to coordinate the project schedule and suppliers. Chapter 5 describes the design of the mechanisms used in the reconfigurable interior, and Chapter 6 discusses the control software, electronics, and validation. Chapter 7 concludes the lessons learned from the construction and testing of this reconfigurable vehicle interior.

Chapter 2: Literature Survey

This chapter will provide an overview of autonomous vehicle development, as well as industry predictions regarding the future of autonomous vehicles. It will discuss some of the implications of this technology, including the design flexibilities and challenges associated with autonomous vehicle interior layouts.

2.1 Autonomous Vehicle Background

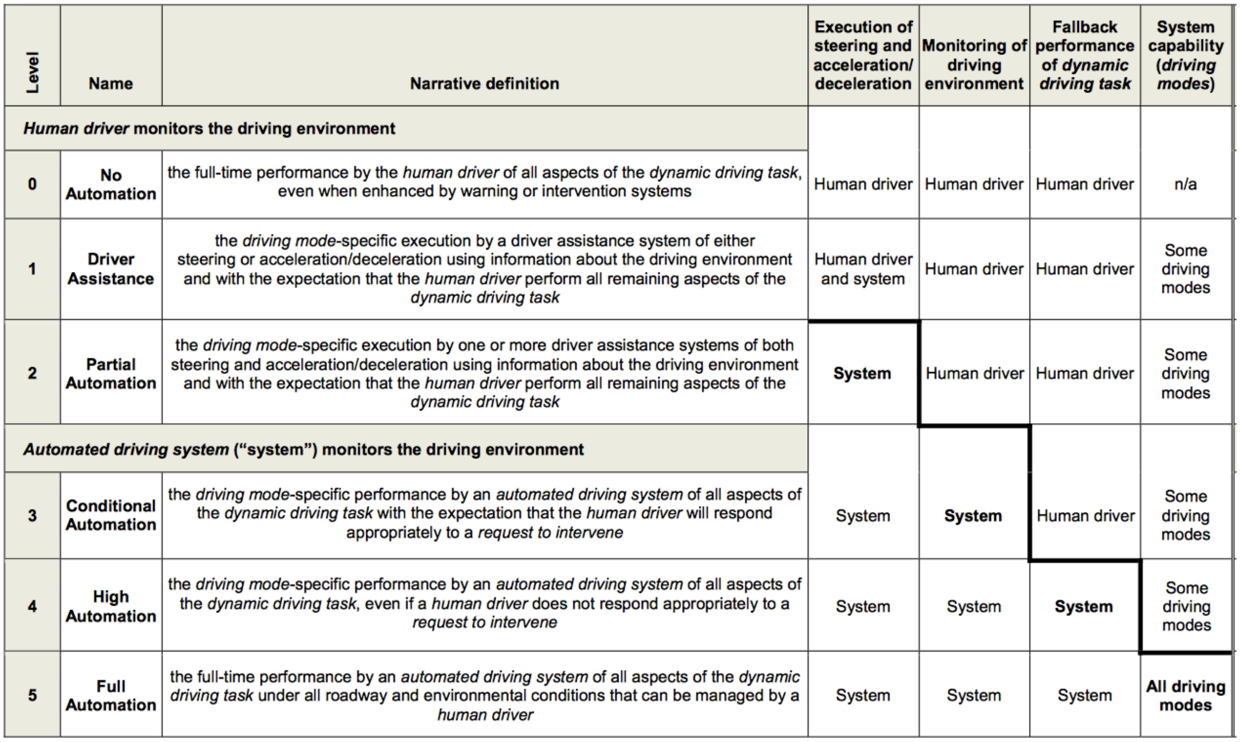
A desire for more free time, fewer motor vehicle deaths, and less road congestion has created demand for vehicles with more advanced driver assistance systems (ADAS) and greater autonomy. According to the US Census Bureau, the average commute time has been rising since the 80's, reaching 26 minutes one-way in 2015 [1]. This is nine days per year that the average American spends commuting. In a self-driving vehicle, this time could be used for work, relaxation, or entertainment.

More concerning than lost time are the deaths and injuries caused by vehicle accidents. In 2017 motor vehicle deaths in the united states are estimated to be 40,000. Injuries from vehicle accidents in the US requiring medical consultation were an estimated 4.57 million in 2017. The cumulative cost of medical expenses, productivity losses, administrative expenses, property damage, and employer costs was $413.8 billion. Many of these crashes may be preventable. An estimated 94% of vehicle crashes are caused by driver error. [2] [3] Automatic emergency braking systems alone could prevent around half of all rear-end collisions [4]. Vehicles with both ADAS systems and vehicle-to-vehicle communication could significantly reduce collision events of all types, even with only partial market penetration [5].

Additionally, autonomous vehicles could improve road congestion. Natural oscillations in human driving can cause unnecessary changes in vehicle speed. This leads to wasted gas and can cause “phantom traffic” where a slowdown of a single car causes a chain reaction in the vehicles behind, leading to a wave of unnecessary slowdowns. Studies from Rutgers University and the University of Illinois have demonstrated that autonomous vehicles can help to smooth the flow of traffic, and improvements were seen when as few as five percent of the vehicles were autonomous. Improving road congestion doesn’t just reduce a driving hassle, it reduces fuel use. Fuel consumption can be reduced by up to 40 percent with the elimination of these unnecessary breaking events. [6]

Finally, autonomous vehicles offer potential societal benefits. Greater mobility could be provided to the young, elderly, or disabled. The number of on-road vehicles could be reduced as autonomy allows for the adoption of ride sharing and car sharing without creating issues of driver shortage. This could result in savings on roadway and parking infrastructure. Insurance and transportation costs could also be reduced due to an accident rate reduction and greater availability of ride-sharing services. [8]

As a result of these potential advantages, automakers are developing vehicles with increasing levels of autonomy. In order to classify these vehicles, the Society of Automotive Engineers (SAE) has defined categories of autonomy. The system categorizes conventional vehicles with no drivers assistance as Level 0. Vehicles with Advanced Driver Assistance Systems (ADAS) are classified as Level 1, 2, and 3, depending on the amount of driver involvement required. Level 4 vehicles have full autonomous capability and do not need driver involvement, but provide the option of manual control. Finally, level 5 vehicles are fully autonomous with no option for manual control. Figure 2 shows these levels. [7]



Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* (“system”) monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2: SAE Defined Autonomous Levels [7]

The rollout of partially automated Level 2 vehicles is happening quickly. Ford, Honda, Toyota, Nissan, and Hyundai all plan to offer Level-2 vehicles capable self-driving on limited access highways by 2020. General Motors is currently offering a Level-2 autonomous vehicle in 2017. By 2030, Daimler, Nissan, General Motors, and Ford all plan to offer Level-4 vehicles. Between 10 and 20 percent of vehicles sold will be level 4 or Level 5 autonomous in 2030 if deployment occurs at a rate similar to other vehicle technologies such as automatic transmission and airbags. [8] [9]

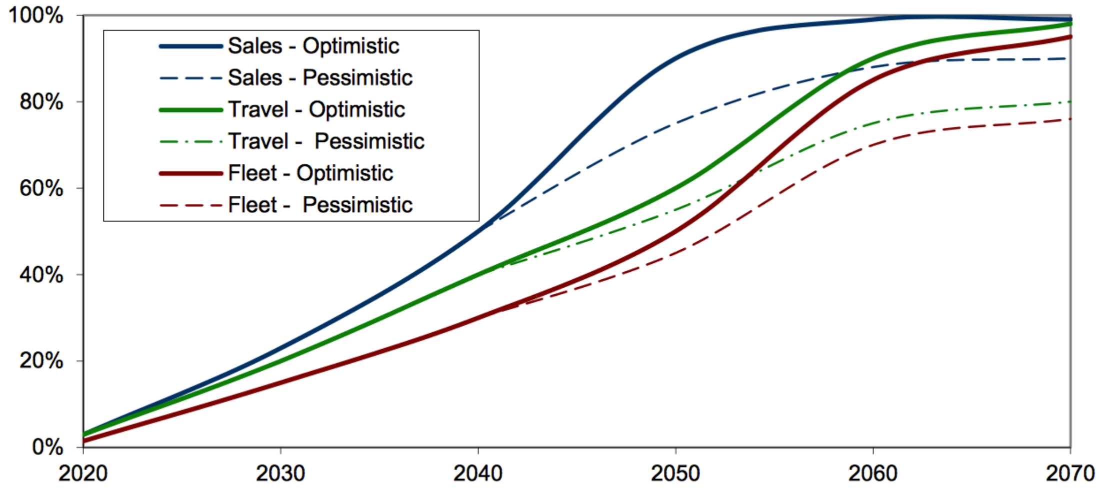


Figure 3: Estimated rollout rate of Level 4-5 autonomous vehicles [9]

2.2 Design Considerations for Autonomous Vehicle Interiors

Autonomy will provide additional design flexibility for vehicle interiors. A Level 5 autonomous vehicle with no steering wheel and pedals, or a Level 4 with ones used minimally, will have more interior packaging options than traditional vehicles. Users may not be required to face forward, and new seating arrangements will become possible [11]. With the user not relegated to driving, autonomy will create hours of free time and an opportunity for additional in-vehicle user experiences. Numerous entertainment, media consumption, and productivity features could all be used to fill the free time during a commute. In multi-user situations, vehicles may be able to offer interiors better catered to socializing than is possible with one user driving. Automakers are just starting to explore how to design for this new “third space” between work and home.

New design constrains will also result from autonomy. Clear and intuitive communication of vehicle mode is a critical design consideration in Level 2-4 [12]. Any confusion about who has control over the vehicle will erode user trust, or worse—cause an accident. Additionally, the attention of a user during a trip will not be reliably directed out windows, at the steering wheel and gauges, and at the front center stack. Directing the user attention to the appropriate place may create challenges, and having user attention not kept reliably in one direction could make it more difficult to achieve high perceived quality from a fit-and-finish perspective.

New business models will also introduce design constraints. Initially, fully autonomous vehicles will be expensive and may be restricted to certain predictable geofenced operating areas. Thus, many of the first Level 4 and Level 5 autonomous vehicles will likely operate for driverless taxi services and other vehicle-fleet business models. Private cars are in use only around 5% of the time, whereas vehicle-fleet business models will have more usage to better cover the additional cost of an autonomous vehicle. A vehicle operating for a driverless taxi service may need to identify itself to ride-share users at it arrives. The vehicle may need to help in directing users to the appropriate seat if the cabin is unfamiliar. Partitioned interiors may become necessary. [10] [12]

2.3 Survey of Autonomous Vehicle Interior Layouts

Several concept vehicles that showcase how other manufactures imagine Level 4 autonomous vehicles will be reviewed here. Although benchmarking was not used in the development of APEX 01, these concepts serve to show the design possibilities of a Level 4 Vehicle and the ways that they may differ from the traditional interior layout.

First is the "Mercedes-Benz F 015 Luxury in Motion" research car, shown in Figure 4. This vehicle has four lounge-style chairs placed into an open pod-shaped body made possible by electric drive. The front two chairs can rotate rearward in order to provide a face-to-face seating configuration shown in Figure 4. The transition between this configuration and a forward-facing configuration has not been demonstrated with people in the vehicle. This four-passenger configuration with rotating front seats is becoming more common in Level 4 autonomous concepts, and appears to be a seating arrangement that many manufacturers are considering. A small central table is placed in the middle of the four seats, helping to break up the space between the occupants when in the face-to-face seating configuration. Control displays are placed on the interior walls of the vehicle, and the vehicle is said to also have gesture-based control. [13]

Figure 4: Mercedes-Benz F 015 Luxury in Motion [13]

Next is the “Budii” concept vehicle, which is based on a BMW i3 donor car. Budii was built by RinSpeed, a small Swiss automobile manufacture and tuning designer. The vehicle has electric blinds which can close when it is chauffeuring you through traffic. While the user is isolated from the outside world, exterior lighting is used so that the car can communicate with other road users. The steering wheel is mounted to a robot arm which can hand the wheel to either front passenger, or fold away when in automated driving mode. The concept also imagines an operating system that considers your habits and preferences, as well those of other Budii cars in the area, to build “experiences.” In this way, the operating system learns and adapts to the user in ways only possible with a connected vehicle. [14] [15]

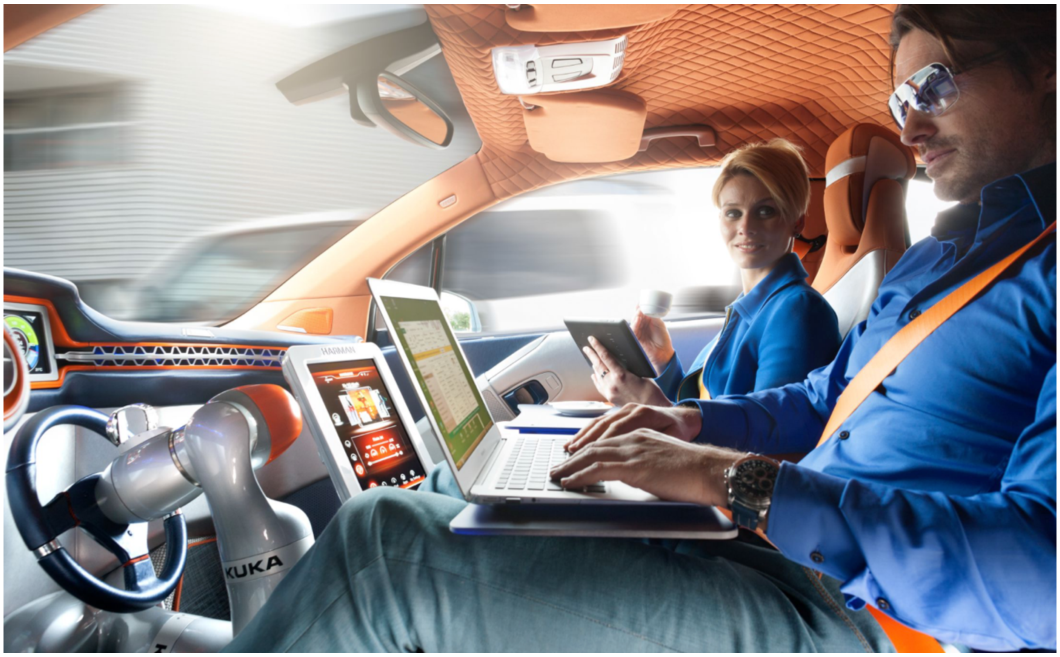


Figure 5: RinSpeed Budii [14]

Finally, Chrysler portal concept showcases a vehicle intended to launch at Level 3 autonomous but later be upgradable to level 4. This vehicle's interior has a front-facing seat layout similar to traditional vehicles, but the "mono-volume" layout made possible by electric drive provides a more open interior atmosphere. With no B pillar obstructing entry, passengers for all three rows of seating can enter at once through the single "portal" that opens, as shown in Figure 6. The steering wheel is capable of folding away into the dash when not in use. [16]

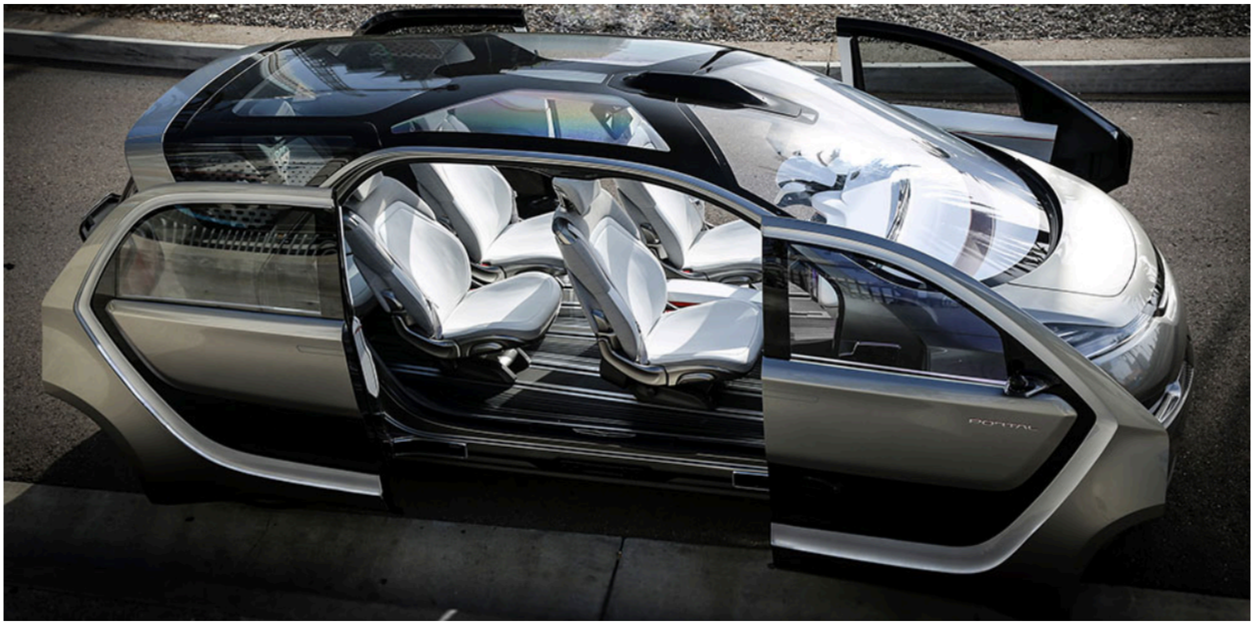


Figure 6: Chrysler Portal [16]

Chapter 3: Concept Development Background

The background research, user persona, user experience scenarios, and initial design direction will be detailed in this chapter. This initial concept development was led by the ArtCenter team, and thus is not an output of this thesis. Instead, the content of this chapter serves to provide background information covering these initial product development steps, as this initial research helped to guide the design and construction of the vehicle interior mockup. This chapter also serves to illustrate the user-first design process used by APEX 01, which focused on the user experience and only investigated technology that enabled this holistic user experience.

3.1 Macro Trend Investigation

In order to design a vehicle for the 2030, research was first conducted to better understand what the market will look like in 2030. ArtCenter students identified macro trends being driven by the Millennial generation. They then researched how these trends were changing over time, in order to select trends likely to increase in the future. They collaborated with Lloyd Walker, a design strategist and futurist, to form a hypothesis of what 2030 might look like. This hypothesis takes the form of 4 trends, which exist currently and the students believe will increase to significantly influence the lives of those living in 2030.

Table 2: Identified Trends

Individual Luxury	Instant Gratification	Entrepreneurial-ish	Access Economy
Luxury that focuses on personalization is gaining traction. Customers are turning away from big labels and choosing custom tailored items, vacations, and experiences that offer more value to their personal brand.	People are becoming accustomed to instant communication and services. This trend will continue to grow stronger as products become more connected. Delays in a user experience will be viewed even more unfavorably than they are today.	New technology platforms are making it possible to earn additional income to supplement the "day job." This entrepreneurship grey area provides additional income but also can cause additional stress and a busier schedule.	Good and services can be exchanged rather than owned. Platforms have immerged to offer people experiences that they would not otherwise be able to afford.

The four trends can be seen in Table 2. Throughout the rest of the design process, the user experience of the vehicle was tailored to fit a culture where these trends are dominant.

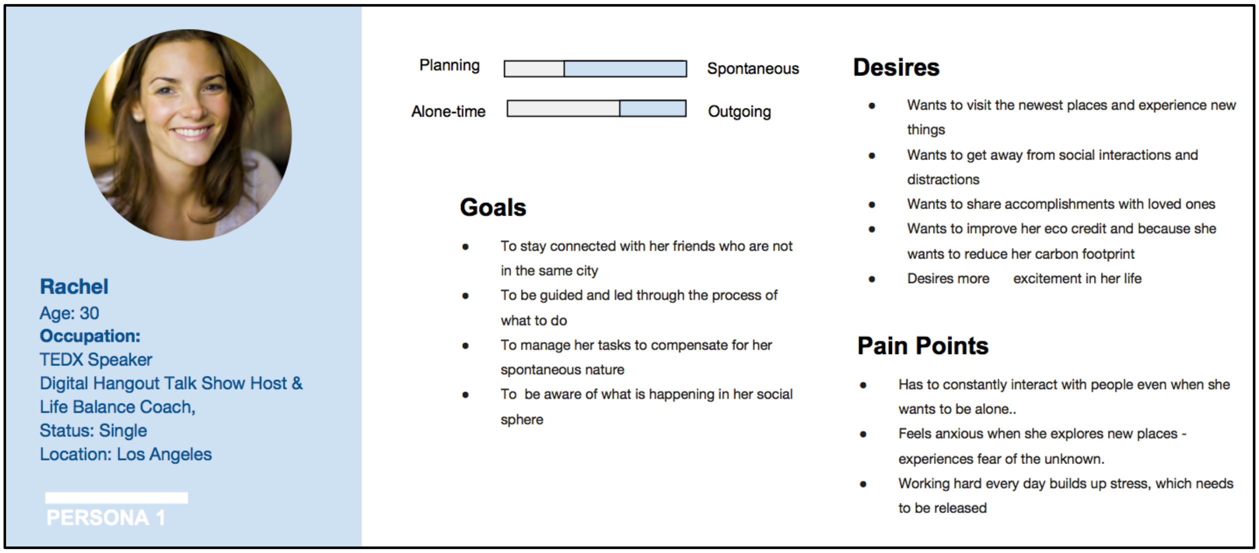
3.2 Core Values, User Persona, and User Clinic

Core values were created to govern the development of use cases. These core values were derived from first and second-hand research of the target customer. ArtCenter students interviewed millennial women about their activities, pain points, and goals. They also researched demographic trends to gain a bigger picture of this customer group. This research resulted in three core values

1) Empowering Self-Improvement
2) Enabling Balance
3) Design for transition

These values provide goals for the vehicle design to meet. The vehicle must be able to help the user improve themselves in ways important to them, be it a desire to be eco-friendlier, eat healthier, or be a better friend or employee. The vehicle also must provide balance to help ease the juggling of a social life, work life, and side jobs. The “third space” offered by an autonomous vehicle offers an opportunity to ease stress and help achieve this balance. Finally, the vehicle’s design needs to consider the transition between experiences, in order to better cater to the Instant Gratification trend identified in section 3.1. This final design goal focus not on the vehicle’s capabilities, but on how best to offer new experiences to the user—how to seamlessly transition into and out of different features.

As an additional tool for developing use cases, a user persona was created. By designing for this persona, the team was better able to generate ideas suitable for the target demographic. Rachel, the name given to this persona, embodies the characteristics identified in the trend research and interviews. Rachel works multiple jobs, and is frequently busy meeting with clients. Balancing all of this can be stressful. She considers herself to be a brand and wants to manage and promote this identity. Rachel was also described as caring for the environment, and having a desire to lower her carbon footprint. Figure 7 shows more characteristics of this persona.



Rachel
Age: 30
Occupation:
TEDX Speaker
Digital Hangout Talk Show Host &
Life Balance Coach,
Status: Single
Location: Los Angeles

PERSONA 1

Planning | Spontaneous
Alone-time | Outgoing

Goals

- To stay connected with her friends who are not in the same city
- To be guided and led through the process of what to do
- To manage her tasks to compensate for her spontaneous nature
- To be aware of what is happening in her social sphere

Desires

- Wants to visit the newest places and experience new things
- Wants to get away from social interactions and distractions
- Wants to share accomplishments with loved ones
- Wants to improve her eco credit and because she wants to reduce her carbon footprint
- Desires more excitement in her life

Pain Points

- Has to constantly interact with people even when she wants to be alone..
- Feels anxious when she explores new places - experiences fear of the unknown.
- Working hard every day builds up stress, which needs to be released

Figure 7: User Persona

ArtCenter students also lead a case study in order to evaluate different interior layouts. A rough plywood mockup of a vehicle interior was built. Different seating configurations were set up inside the plywood mockup. These seating configurations included standard forward-facing seating, a face-to-face configuration as seen in the Mercedes-Benz F 015 Luxury in Motion research car, and several other non-standard arrangements. Study participants from the college experienced the different seating configurations and were interviewed about their preferences.

A few observations were gained from this case study. First, the majority of the participants did not like the idea of traveling backwards. They felt that in an autonomous vehicle it would be unnerving to be driven in a direction opposite the direction you were facing, and noted that facing backwards would make it impossible to glance at the road out front. This suggests that the rotating front seats commonly seen in autonomous vehicle concepts may be uncomfortable for some users. Second, several participants reported feeling awkward when in face-to-face seating configurations, and some felt those configurations were reminiscent of public transportation. Finally, despite voiced concerns regarding face-to-face seating and facing opposite the direction of travel, participants still wanted a way to converse with fellow passengers without turning to look behind them as necessitated in the traditional vehicle layout. This feedback helped to guide the seating configuration that was eventually selected in Section 3.4.

3.3 User Experience Scenarios

The next step in the design of the APEX 01 interior was developing user experience scenarios. These scenarios were used to guide the design and were used to identify features that should be implemented. The order of steps taken in this process should be noted: the user experiences were created first, and only after this step was the shape and form of the interior created and possible technology investigated. The user experience of a traditional vehicle is already known to be predominantly driving, but the user experience could not be assumed with a Level 4 vehicle, as no such vehicle exists on the market yet. This necessitated the design process used by APEX 01. Four user experience scenarios were created that aligned with the core values and fulfilled the needs of the user persona.

The first of these experiences can be seen in Figure 8. In this scenario the user, Rachel, is driving home on a scenic road. She receives a call from a friend who is stuck commuting in traffic. The vehicle recognizes that the friend would like to escape traffic and join Rachel on the scenic road, and offers the two a shared driving experience. This experience allows Rachel and her friend to feel that they are together in Rachel's car, and Rachel's friend can feel the sensations of wind and smell of the ocean remotely from her vehicle. At the end of their commute, the vehicle offers them both the change to archive this experience for later playback. In this scenario, the vehicle helps the user balance her social life with her busy schedule by providing a social experience in what would otherwise be a solo commute.

01: Rachel has just finished hosting her show for the day, it was hectic and she is feeling a bit stressed out; she spontaneously decides to go on a drive along Pacific Coast Highway.

02: Rachel is in the car. She is driving on PCH to relieve her stress.
At the same time, her friend is another car, she is stuck in L.A. traffic.

03: Rachel's friend pings her " Hey Rachel What's up! "
Rachel : " I'm enjoying my drive along PCH , what about you? "

04: Friend : " Nice! I'm stuck in LA Traffic ! "
Car asks Rachel " Do you want to share your driving experience with your friend?

05: Rachel sends out an invitation to her friend to share her experience.
Now, her friend can experience what Rachel is experiencing even though she's stuck in the Traffic.

Her friend asks Rachel " Can I join you in driving ?"
They then decide to the level of Shared Experience.

06: Her friend's hand pops up on Rachel's steering wheel hologram showing that they're driving together.

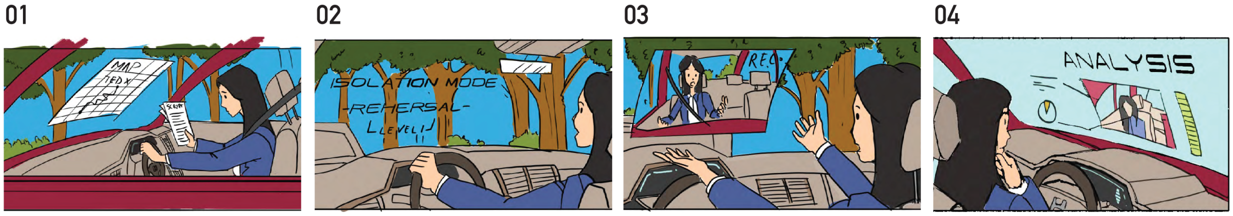
Rachel and her friend starts driving Rachel's car together.

This is the true shared driving experience.

07: At the end of the trip, both their Acura's ask them if they want to archive the experience.

Figure 8: Shared Driving User Experience

In the second scenario, Rachel is heading to give a presentation. The vehicle knows her schedule and recognizes that she is stressed. It offers to drive her so she can practice her presentation, and it analyzes her practice session to help her improve. Next, the vehicle transitions to an "isolation mode" where the exterior environment is blocked out and a virtual reality stage is displayed on the windows in order to provide a more realistic practice environment. As she nears her destination, the vehicle gradually fades the isolation effect of the windows, and when she exits the vehicle her mobile device asks if she would like to save the notes that she made during the drive. This experience was offered based on context, not the selection of a menu item, and it extends beyond the exit of the vehicle. This embodies the Design for Transition core value.



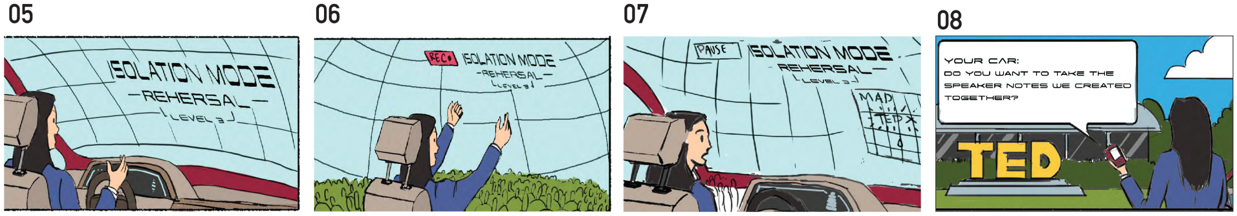
Today, Rachel has to give a TEDx Talk.
However, she has not prepared well enough.
She wants to rehearse her speech on the way to the event.

She chooses to rehearse her speech in the car.

Car recognizes that she needs to be isolated as well, hence the car turns on 'Isolation Mode '.
Rachel commands car to engage ' Rehearsal Mode '.

She starts to practice her speech and car records it. (Level 1 of help)

She wants to check how she did.
She gives a command to the car to review her speech (ie. increasing the level of input from car)



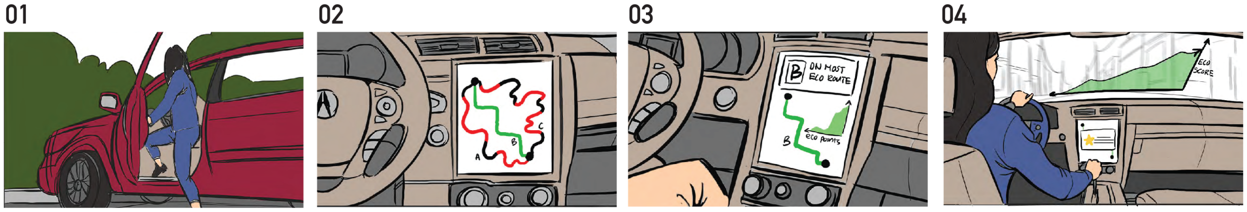
After making edits and changes, she decides she wants to practice again.
This time she increases the input again.
For example, higher level of experience so that she can practice like how it's going to be in the real experience

Car provides an environment like TED Talk stage. (Full immersion practicing her speech) with VR view.
While she continues rehearsing, car almost arrives at the TEDx venue.
Car provides transition between VR view and the real mode(fade out) based on location.
Car 'transitions' out of the isolation mode

Car asks " Do you want to take the speaker notes?"
Her speaker notes get automatically updated into the final presentation as she arrives at the venue

Figure 9: Presentation Practice User Experience

The third user experience can be seen in Figure 10. Here, the vehicle provides route selections based on an "Eco Credit Score" to help inform Rachel about the environmental impact of each of her possible choices. As motivation for her to improve in this area, which the vehicle knows she values, it offers her a premium parking spot as a reward for her eco-friendly route selection. This gamification of a goal demonstrates the Self Improvement core value.



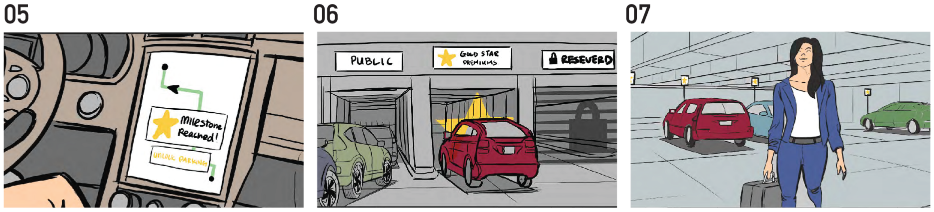
Rachel is an environment friendly person motivated to improve her Eco-Credit Score which will gain her access to certain routes and parking spots designated to those with a High Eco-Score.

Rachel is on her way to visit with a client.

Car Suggests Rachel available routes where she can improve her Eco Credits Score.

Rachel picks Route B because that allows her to improve her Eco Credit Score by maximum.

Rachel is able to see her Eco Credit Score improve.



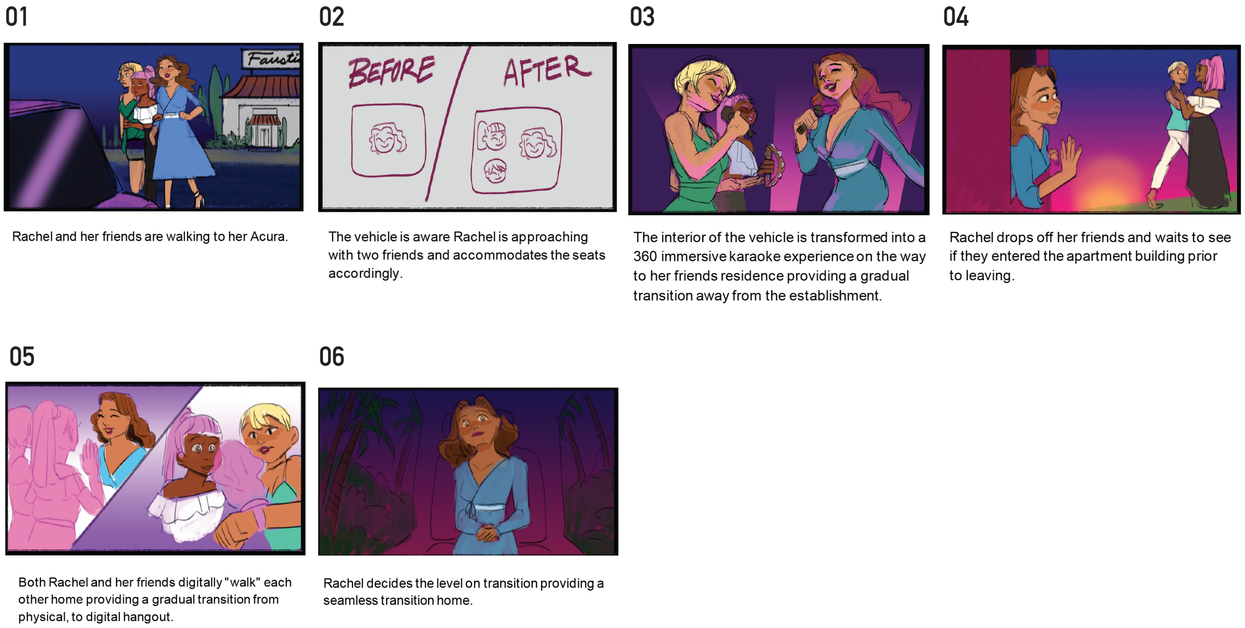
Car shows that she's reached new Eco-Score milestone. Car shows that she has access to new places and locations

Car is showing Rachel that she's getting the privileged parking spot.

She leaves her car and feels happy and motivated.

Figure 10: Eco Credit Score User Experience

The final user experience, shown in Figure 11, is a multi-user scenario where Rachel and her friends are having a night out. As they approach, the vehicle recognizes that there are additional passengers, and reconfigures the interior accordingly. The vehicle knows they've been out dancing, and offers a karaoke environment so they can continue the festivities on the ride home. Upon arrival to the friend's apartment, the vehicle provides an audio and visual connection between Rachel and the friends as they exit. This helps Rachel know that they've reached their front door safely, as well as providing a seamless transition from physical to digital interaction.



01 Rachel and her friends are walking to her Acura.

02 The vehicle is aware Rachel is approaching with two friends and accommodates the seats accordingly.

03 The interior of the vehicle is transformed into a 360 immersive karaoke experience on the way to her friends residence providing a gradual transition away from the establishment.

04 Rachel drops off her friends and waits to see if they entered the apartment building prior to leaving.

05 Both Rachel and her friends digitally "walk" each other home providing a gradual transition from physical, to digital hangout.

06 Rachel decides the level on transition providing a seamless transition home.

Figure 11: Karaoke and Virtual Presence User Experience

3.4 ArtCenter Design Output

This section will show the design direction provided by ArtCenter students to the Ohio State team.

First, Figure 12 show a rendered view of the exterior when in entry mode. This render shows the interior before refinements were made for ergonomics and usability. The vehicle design is street-side entry only, with a single large opening and no B pillar. This was chosen because the vehicle is intended to pick passengers up from the side of the road, with parking handled by the vehicle alone. To aid entry, ArtCenter's design also features a lifting roof—not shown in the render. This lifting roof allows all four passengers walk into the vehicle without ducking.

Figure 12: Entry Mode Exterior Render

After the design shown in Figure 12 was produced, the Ohio State team collaborated closely with the ArtCenter team in order to refine the design. The design was altered to improve feasibility and to fit the layout within the footprint of an Acura MDX. Changes were made to the interior's CMF (color material and finish) to better fit the intended audience and available materials. Armrests were added for all passengers, storage was added to the dash area, and the aesthetics of the steering wheel were improved. The disappearing rear seat was kept, as it created an easily accessible luggage location when folded, but improvements were made to improve the comfort of rear seat passengers when deployed. The Figures 13-14 show two seating modes possible with the refined design.

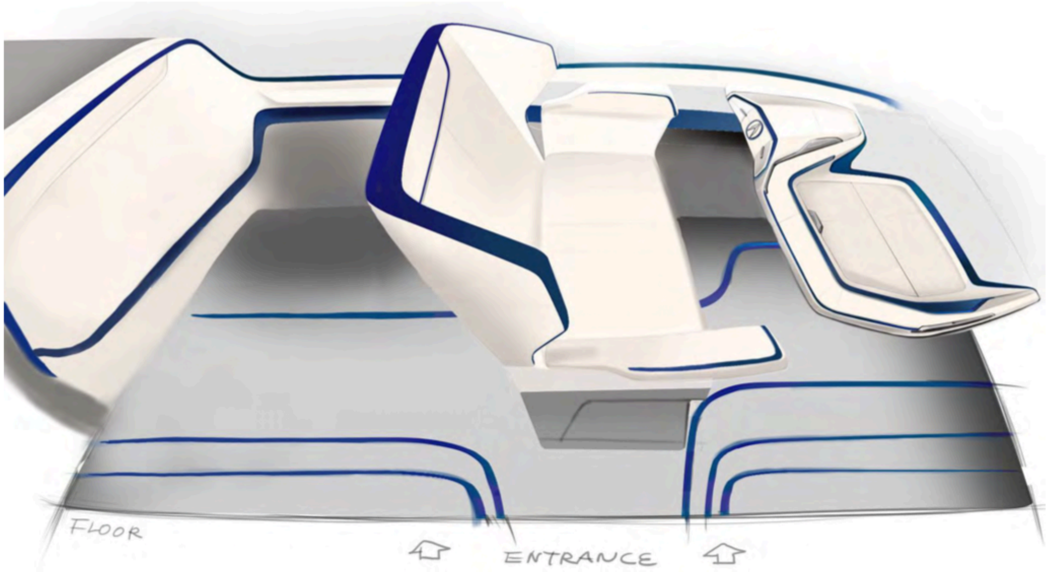


Figure 13: Forward-Facing Seating Configuration Sketches

In Figure 13, the forward-facing seating configuration with the rear seat retracted is shown. This is the default mode when only a single passenger is in the vehicle, and is also the configuration used for manual driving. When this seating mode is being used, the seat rotates clockwise 45 degrees in order to ease ingress and egress, as rendered in Figure 12.

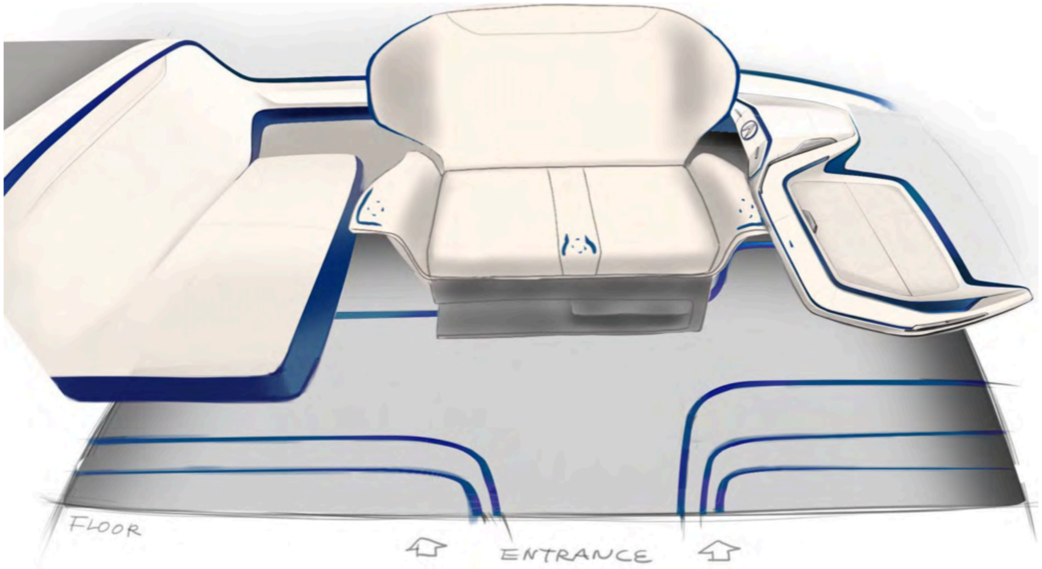


Figure 14: Multi User Seating Configuration Sketches

Figure 14 shows the seating when reconfigured to form a lounge-like “fire side chat” environment. With the front seat rotated 90 degrees clockwise and the rear seat extended, a social space for up to four people is created. This “L” seating configuration has some unique advantages over the configurations shown in existing concept vehicles. Unlike other seating arrangements, no passengers ride backwards in this configuration, yet natural conversation can still occur. In user clinics, people found this seating to be less reminiscent of public transportation. Passengers from all seats have visibility out the front windscreen in order to check on the environment outside. Lastly, the front seat can rotate while occupied without interference. The front seat passengers have plenty clearance for their legs when the front seat rotates between driving and social modes—something that is not typical for layouts where the front seats rotate 180 degrees.

The layout also avoids the face-to-face environment that was found to be potentially uncomfortable during the user clinic. The rest of the interior was designed to shed the notion of a “car,” and instead create a “room” conducive to socializing when in this seating configuration. The low dash is positioned as a side table, and the windows on the right side of the vehicle can display content, e.g. television, for the passengers.

Figure 15: Seat Concept Sketches

Figure 15 shows additional views of the moving front seat that highlight another reconfigurable element of the interior: the moving armrest. The two front seats are joined in one lounge-style couch to create a relaxing and comfortable environment. This front couch can be divided into two front seats by extending the middle armrest. This provides additional separation between front passengers when needed, and is desirable for the upright posture of manual driving. The front seat also has control points built into the armrests which activate when a user sits down. This makes the controls accessible in any seating mode, and lets users enter inputs without having to lean forward to access controls.

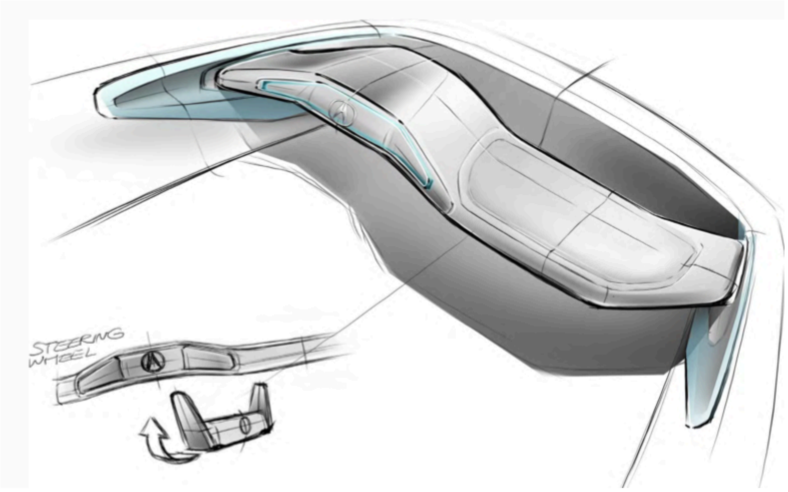


Figure 16: Dash Concept Sketch

Figure 16 shows the final aesthetic design of the floating dash and steering wheel. The steering wheel has handles which rotate in order to fold flat into the thin dash. This allows for a dash that closer resembles a piece of furniture. The right side of the dash forms a storage area.

Chapter 4: Project Management

APEX 01 required the coordination of several suppliers in order to complete the reconfigurable interior. This chapter will discuss the project goals, division of work between suppliers, and the project timeline that was used to organize the project.

4.1 Project Goals

In order to design the reconfigurable interior, specifications were needed in addition to the sketches provided by the ArtCenter team. To generate performance metrics for the reconfigurable interior, two of the user experiences discussed in Section 3.3 were choreographed: The Presentation Practice, and Karaoke and Virtual Presence scenarios. The desired seamless user experience was planned and the timing for each interaction and experience was recorded. Then the timing of every item in the mockup was added to fit the timing of this user experience. The motion of the doors, roof, front seat, rear seat, and steering was planned such that the movement of those mechanisms was rapid enough not to cause any pauses in the experience. The results can be seen in Table 3 and the full choreographed user experiences are shown in Appendix 1.

Table 3: Mechanism Motion Speed Targets

Mechanism Motion	Speed Target (seconds)	Passenger Load
Rear Seat Extension	7	n/a
Front Seat: Entry to Forward-Facing and Forward-Facing to Entry	4	2 in Front Seat
Front Seat: Forward-Facing to Social and Social to Forward Facing	7	2 in Front Seat
Front Seat: Armrest	3	0
Steering and Pedal Retraction	6	n/a
Roof: Open to Closed and Closed to Open	7	n/a

The seating layouts show in the sketches were drafted in SolidWorks and measurements were taken of the seat positions. These measurements were used to defined the required motion of the mechanisms. The rear seat extension was found to be 16 inches. The front seat motion can be seen in Table 4.

Table 4: Front Seat Mechanism Position Targets

Position Name	Translation (in)	Rotation (degrees)
Driving, furthest forward position	0	0
Forward-Facing, centered in cabin	18	0
Entry	10	45
Social	6	90

4.2 Division of Work

The reconfigurable interior was divided into elements: upper frame, lower frame, dash and pedal mechanisms, front seat mechanism, rear seat mechanism, and roof mechanism. In order to complete the project in a short timeframe, several suppliers were used for design and fabrication support. Their roles can be seen in Table 5.

Table 5: Supplier Roles

Supplier	Role	Input	Output
Additive Engineering Solutions (AES)	•Front seat base construction	•STL File	•3D printed (FDM ABS) seat base
Goken America	•Upper frame design •Roof mechanism design •Rear seat design	•Window locations •Roof geometry and speed requirements	•BOM •CAD design
Center for Design Manufacturing Excellence (CDME)	•Design support: front seat mechanism •Fabrication support: front seat mechanism, upper frame, roof mechanism, and rear seat	•Seat position and speed requirements •BOM and CAD from Goken America	•Continuous Design and Fabrication support throughout development

Honda Research Americas	•Manufacturing and paint of dash pieces	•STL Files	•3D printed (SLS nylon) and painted dash pieces
Honda LA	•Front seat fabrication and upholstery •Rear seat bottom upholstery	•CAD designs •Fabric stock	•Upholstered front and rear seats

4.3 Project Timeline

The output of each supplier, as well as the contributions from two interns, had to be sequenced to match the order of assembly and allow for a manageable workload for the OSU team. A simplified version of the timeline created to organize this work can be seen in Figure 17. The timeline was continually updated as the lead time of various components were defined. The final interior mockup was demonstrated on May 12th.

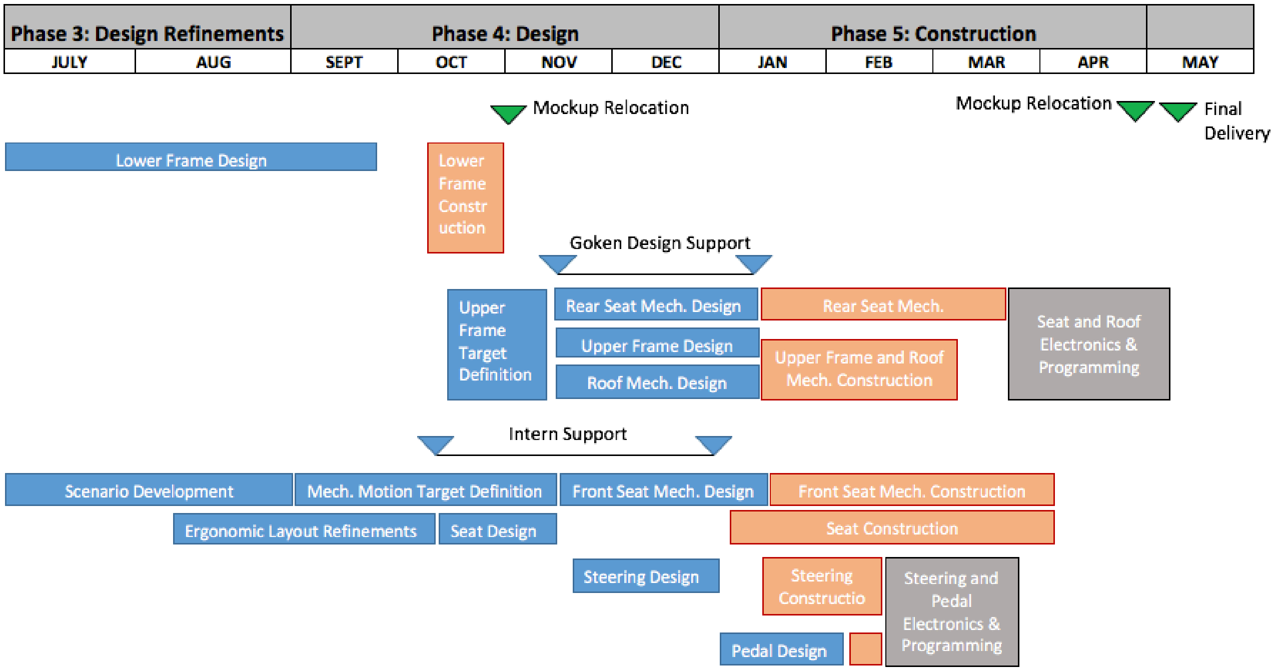


Figure 17: Reconfigurable Interior Timeline

Chapter 5: Mechanism Design

This chapter will cover the design of the folding steering wheel, folding pedal, and moving front seat. The design of the rear seat and roof mechanism was completed by Goken America based on OSU's design requirements, and will not be discussed in this thesis.

5.1 Retractable Steering Wheel Design

A folding steering wheel and dash were designed and constructed based on the sketch shown in Figure 16. The resulting steering wheel can be seen in Figure 18 in both the retracted and extended state.

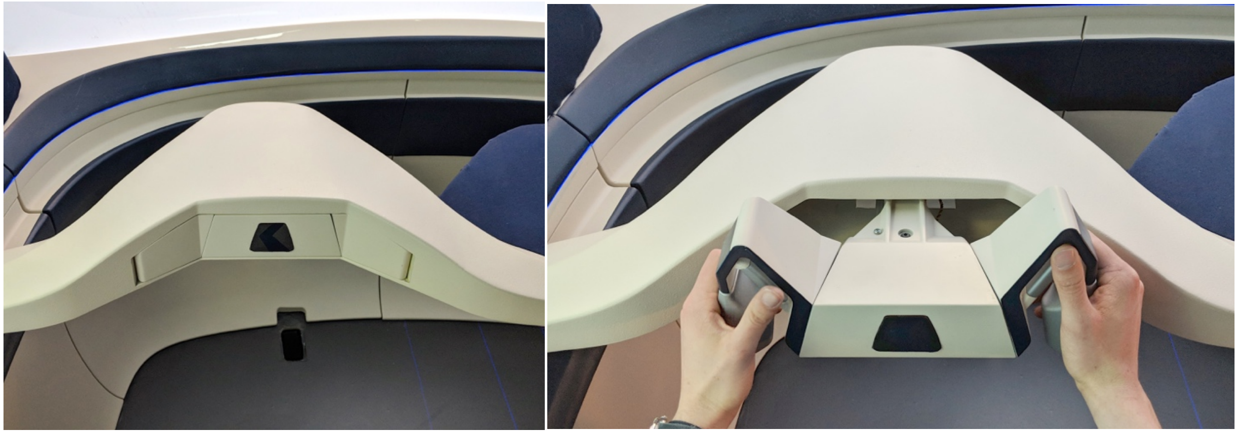


Figure 18: Steering Wheel

Based on the experience choreographed, the time requirement for the steering retraction was 6 seconds or less. Only retraction speed was important for the planned demonstration experience. Size constraints were created due to the thin dash guided actuator selection. For the extension and retraction of the steering wheel, a 140mm stroke length L12-R micro linear servo produced by Actuonix was selected, as it was compact (12mm x 12mm cross section) and lightweight (56 grams). The built-on position feedback was also desirable. The 140mm stroke provided sufficient offset from the dash to place the steering wheel in a natural position when deployed.

The 50:1 ratio of the linear servo was selected, which provided only 22N (5lb) of force but allowed for a 25mm/s unloaded actuation speed. This 4 second travel time suggested that the actuator would meet the 6 second retraction speed requirement, especially given that the actuator's motion would be assisted by gravity during retraction. The steering wheel hub was bolted to a linear slide, with the actuator pinned to the slide base on one side and the steering wheel hub on the other. The linear slide and actuator were angled upwards by 7 degrees. Because the actuator was mounted using pins, it was not subject to off-axis loading.

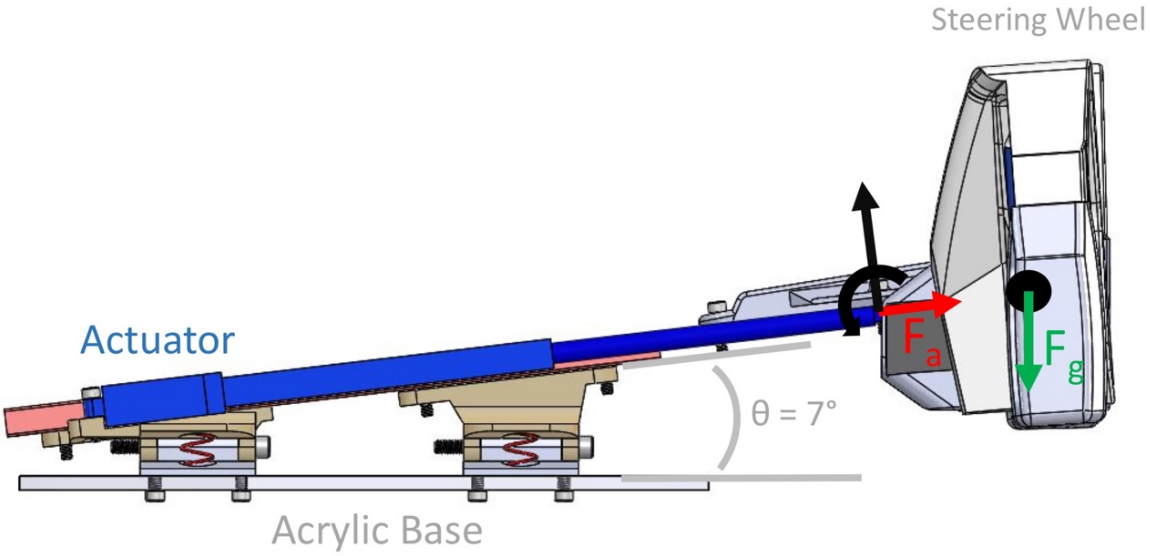


Figure 19: Steering Extension, Left Side View

The free body diagram of the steering wheel extension mechanism shown in Figure 19 served to check if the 22N actuator force of the actuator was sufficient. F_a refers to the force applied by the actuator, F_g refers to the gravitational force, and the black arrow and moment refer to the support provided by the linear slide. Given the 7-degree angle of the linear slide, the compression force on the actuator when the wheel is held in a static position is:

$$Actuator\ Force = Sin(7°) * g * mass_{wheel} \tag{1}$$

Thus the mass of the steering wheel can be 22N/(9.8* $Sin(7°)$) = 18.4 kg before the wheel would be unable to extend, assuming zero friction with the linear slide. As the expected mass of the steering wheel was less than 1 kg, this was well within the capabilities of the actuator.

The linear slide was mounted to a pair of 3D printed mounts. These mounts could rotate 22 degrees in either direction. This allowed the steering wheel to turn when deployed. Although minimal compared to a real vehicle, the 44 degrees of total rotation was enough to demonstrate the concept. Figure 20 shows a front view of these mounts.

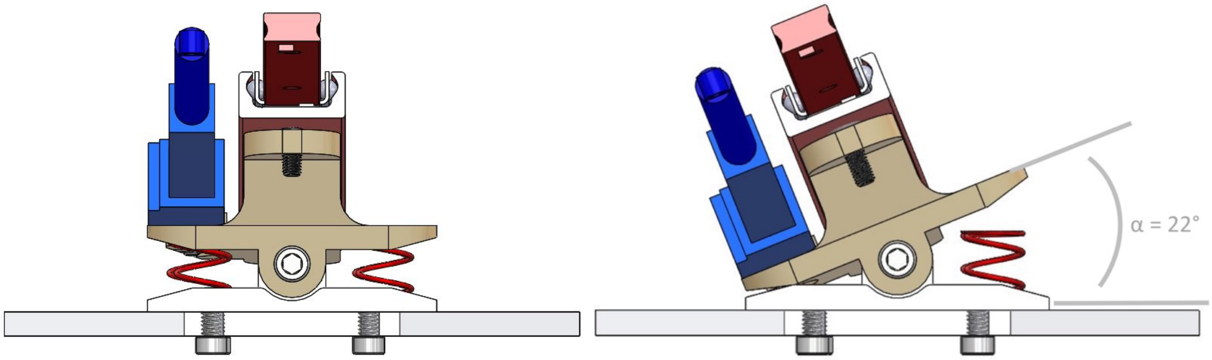


Figure 20: Steering Mounts, Front View

To return the steering wheel mounts to center after rotation, a pair of compression springs were used for each of the two steering mounts. These compression springs were fastened to the baseplate, but not the steering mounts, so only the spring being compressed was engaged when the steering wheel was turned. All four springs were at their neutral position when the wheel was centered.

Although springs were needed to return the steering wheel to center, they could not interfere with demonstrating the steering wheel. A .2589 kg/mm (14.5 lb/in) spring rate was selected for these compression springs. At full rotation, the springs were compressed by 7mm. Both compressed springs were offset by 20.5mm from the pivot point. Thus, the two compressed springs would cause a moment of 74 kg-mm (5.3 lb-ft) at 22 degrees of rotation, as calculated in equation 2. This resistance was the maximum possible within the range of motion, and was considered reasonable for the mockup steering wheel.

$$Moment = 2 * k * \Delta d * offset = 2 * .258 \frac{kg}{mm} * 7mm * 20.5mm = 74kg * mm \qquad (2)$$

With the steering wheel extension and rotation accounted for, attention was turned to the handles. As per the ArtCenter sketch, these handles were to unfold as the wheel extended. The handles were designed to best replicate the motion shown in Figure 16, and the result can be seen in Figure 21.

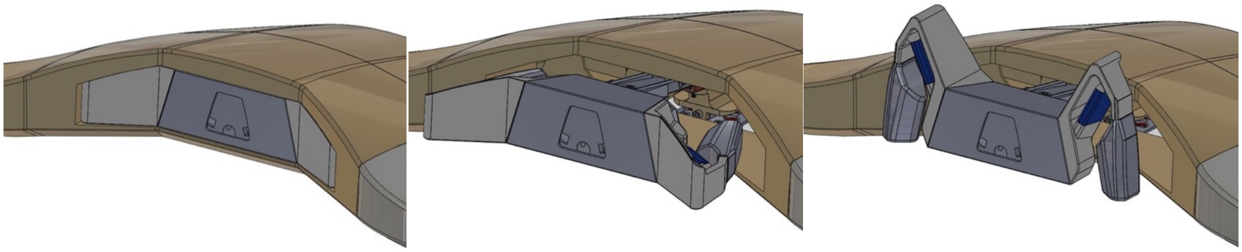


Figure 21: Steering Wheel Handle Deployment

In order to achieve the motion shown in the sketch, the pivot axis of the handles was not horizontal. The pivot axis was angled upwards and away from the driver, off the Y axis by 21 degrees. This was necessary so that the tops of the handles rotate upwards, positioning them above the wheel center when deployed. Figure 22 shows an approximation of the right handle axis of rotation, and the left handle axis is simply the mirror over the XZ plane.

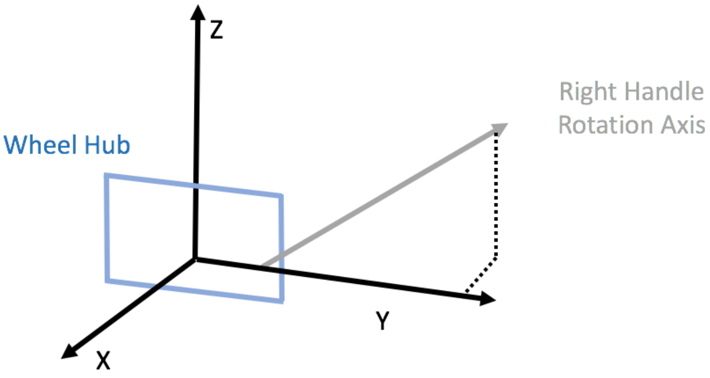


Figure 22: Steering Wheel Handle Axis of Rotation

Heavy-duty hobby servos were chosen to actuate the rotation of the handles, as the built-in position feedback allowed for simple control. Hi-Tec HS-805BB servos were selected, which were the largest size servos that could fit within the width of the steering wheel hub. These servos were designed for 1/4th scale model vehicles, and provided 24.7kg.cm (343.01 oz/in) of torque. This was more than enough to rotate the lightweight (< .25 kg) handles, and sufficient for holding them in place during use if needed. A pocket was added to the mounting surface of the handles to conceal the servo horn.

5.2 Retractable Pedal Design

To complement the folding steering wheel, a folding pedal was added. Only one pedal was needed to demonstrate the folding concept. The pedal used the same 50:1 L12-R micro linear servo as the steering, just with a 50mm stroke length. The decision to use the L12-R micro linear servo came after successful testing of the steering wheel, and based on this prior experience it was correctly assumed that the actuator would be sufficient for actuating this lightweight pedal.

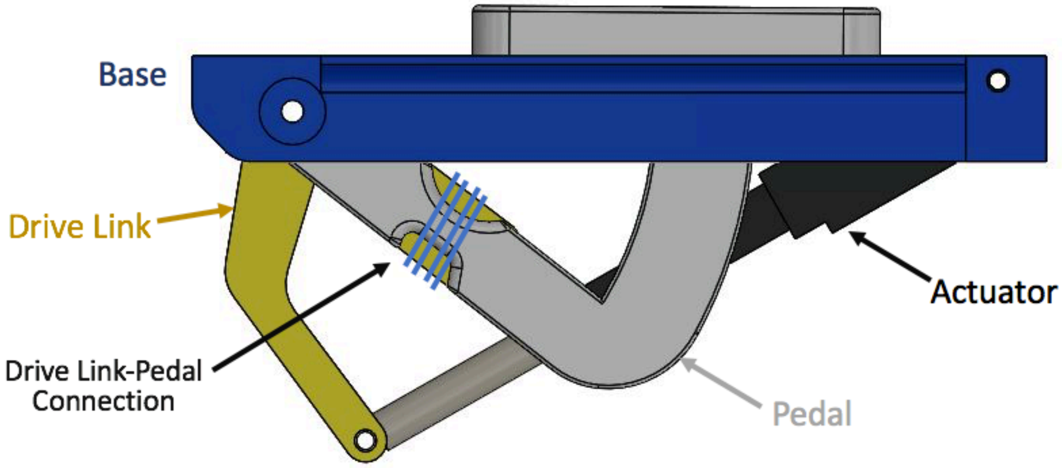


Figure 23: Folding Pedal Mechanism, Retracted

The design of this pedal can be seen in Figure 23 in the retracted configuration. In this position, the linear servo is fully extended, which rotates the drive link clockwise relative to the view seen in Figure 23. The pedal is passively coupled to drive link using rubber bands. When the drive link is in this position the pedal is pulled flush with the floor. When the linear servo retracts, the drive link rotates counter clock wise which deploys the pedal. Because the pedal is only passively coupled to the drive link, a user can step on the pedal and it will move as expected without applying a large force to the actuator.

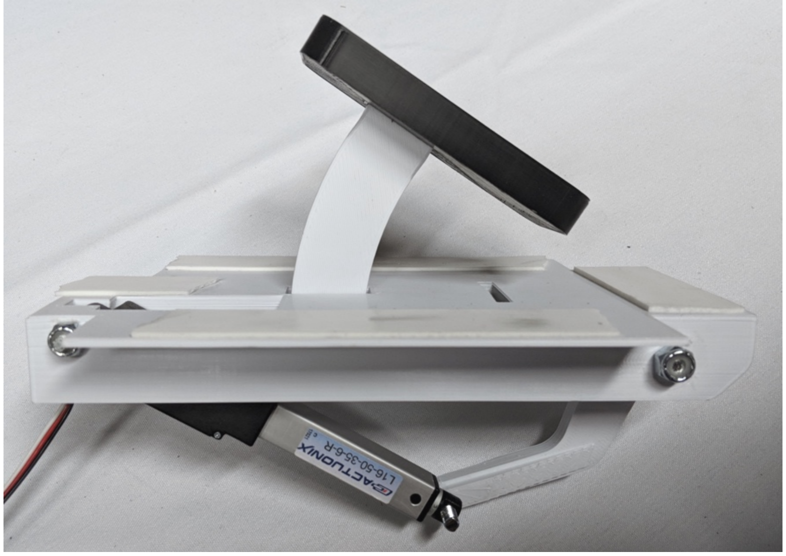


Figure 24: Folding Pedal, Extended

Figure 24 shows the pedal during assembly. All parts were 3D printed from ABS. The pedal and drive link both rotate about the same bolt, attaching them to the base. This simplified assembly.

5.3 Front Seat Mechanism Design

The reconfigurable front seat had three separate movements: linear motion, rotation, and armrest deployment. The linear and rotation motions will be discussed in this section.

When the seat positions shown in Section 3.4 were provided, the first goal was to achieve these desired positions with only two degrees of freedom. This would reduce complexity and make for an easier to fabricate mechanism. First, linear front-to-back motion was identified as a requirement in order to accommodate various driving positions and the forward-facing, centered in cabin position. This motion was required to be independent—the seat could not rotate or move laterally while moving front-to-back.

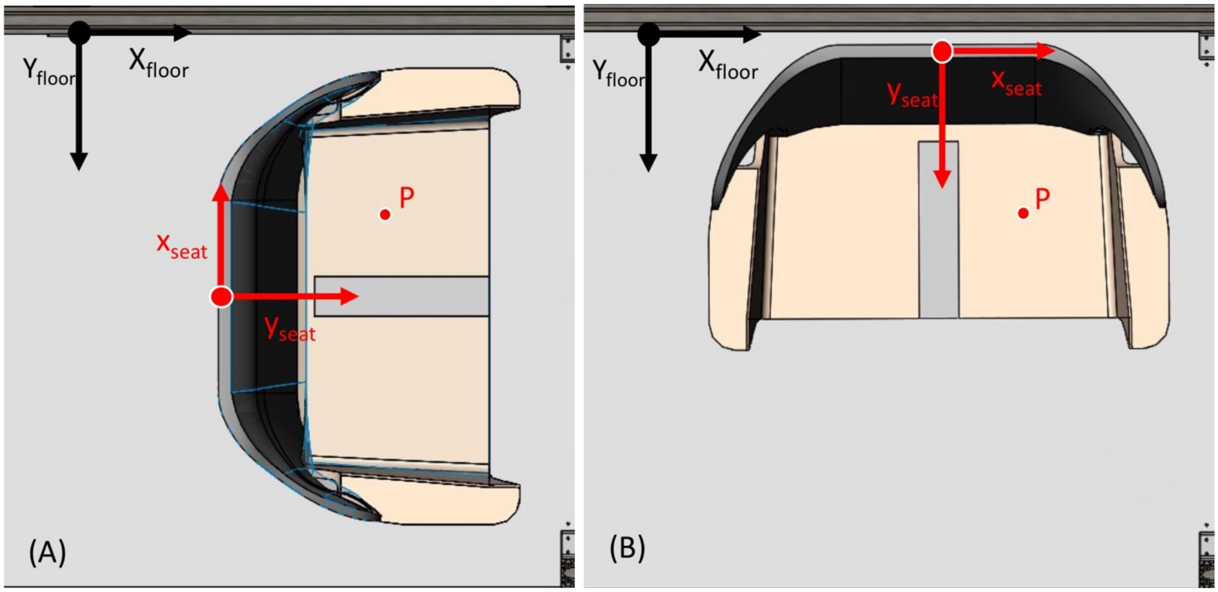


Figure 25: Front Seat Positions: Forward-Facing (A) Social Configuration (B)

Next, the social mode seat position was addressed. To achieve this position, shown in Figure 25 (b), the front seat was to rotate 90 degrees clockwise and move to the left side of the cabin. These two motions did not need to occur independently to achieve any of the other seating modes, and so were coupled together. An off-center axis of rotation was selected in order to move the front seat to the left as the seat rotated clockwise.

Simple geometry was used to find an acceptable location for the rotation axis, (P_{x_seat}, P_{y_seat}) relative to the seat coordinate frame, as well as the axis offset from the left frame wall, P_{Y_floor}. The seat origin was described as aligning with the seatback and center plane. While in the social mode, the seatback had to have an offset from the left side frame rail for proper clearance from the interior body panels, so:

$$P_{y\_seat} + Offset_{left\ rail} = P_{Y\_floor} \tag{3}$$

When in the forward-facing configuration, the seat was to be centered within the cabin:

$$\frac{1}{2} Width_{cabin} = P_{x\_seat} + P_{Y\_floor} \tag{4}$$

Figure 26 shows possible pivot axis locations resulting from Equation (3) and (4), with the corresponding axis offset, P_{Y_floor}, labeled. The desired seatback offset was 27mm and the cabin width was 1498mm.

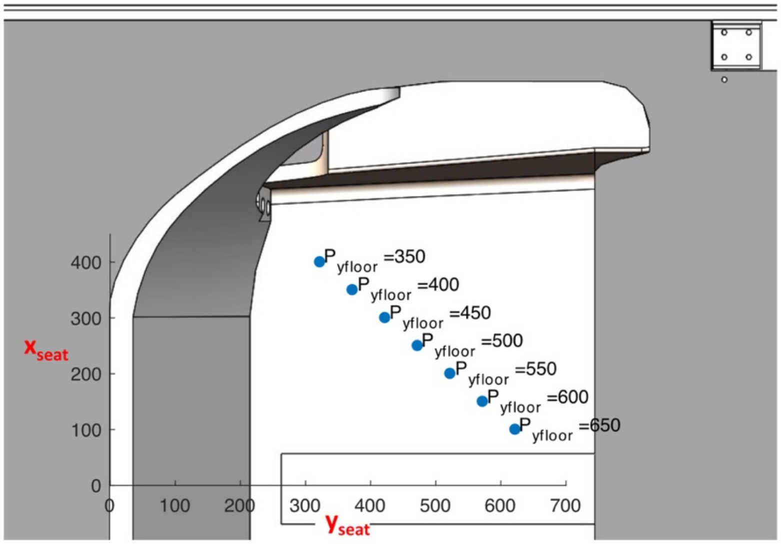


Figure 26: Possible Front Seat Axis Locations

The back-left corner of the seat had to clear the side frame rail by when rotating between positions. This final constraint allowed an axis location to be selected. The 45-degree clockwise rotation position was used to check for this clearance. The seat corner was defined by point C located at (448mm, 8mm) relative to the seat base.

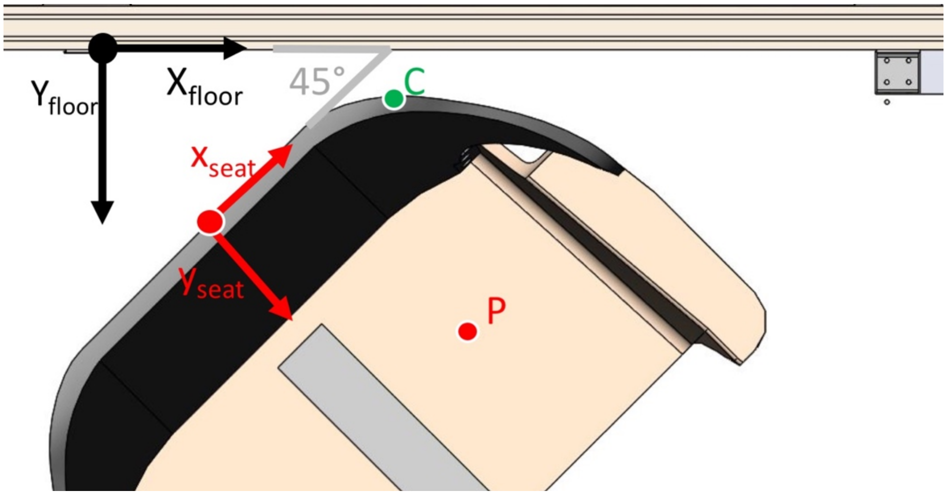


Figure 27: Front Seat Corner Clearance Check

From this, corner clearance can be found from P_{x_seat}, P_{y_seat}, and P_{Y_floor}:

$$Offset_{corner} = P_{Y\_floor} + \sin(45)\,(8mm - P_{y_{seat}}) + \cos(45)\,(P_{x_{seat}} - 448mm) \qquad (4)$$

Using this offset equation, an axis of rotation location was chosen, P_{Y_floor}= 511mm for a location of (238mm, 484mm) relative to the seat origin. This location had an acceptable corner clearance of 26mm. Figure 27 shows the clearance check and selected axis location.

With the geometry complete and motion requirements known, the front seat mechanism shown in Figure 28 was designed with the help of CDME. This mechanism achieved the “floating seat” appearance set by the design direction. The seat was divided into an upholstered upper seat, and a structural seat base. The seat base was attached to a T-shaped sliding seat support via a heavy-duty turntable. The sliding seat support was mounted to the prototype frame using linear bearings, and an 18” liner actuator slid the support front-to-back. Caster wheels riding on a steel plate integrated into the floor were used to support the end of the sliding seat support with the turntable. A second 10” linear actuator pinned to the sliding seat support and seat base was used to rotate the seat base. The assembly included two potentiometers to provide position feedback.

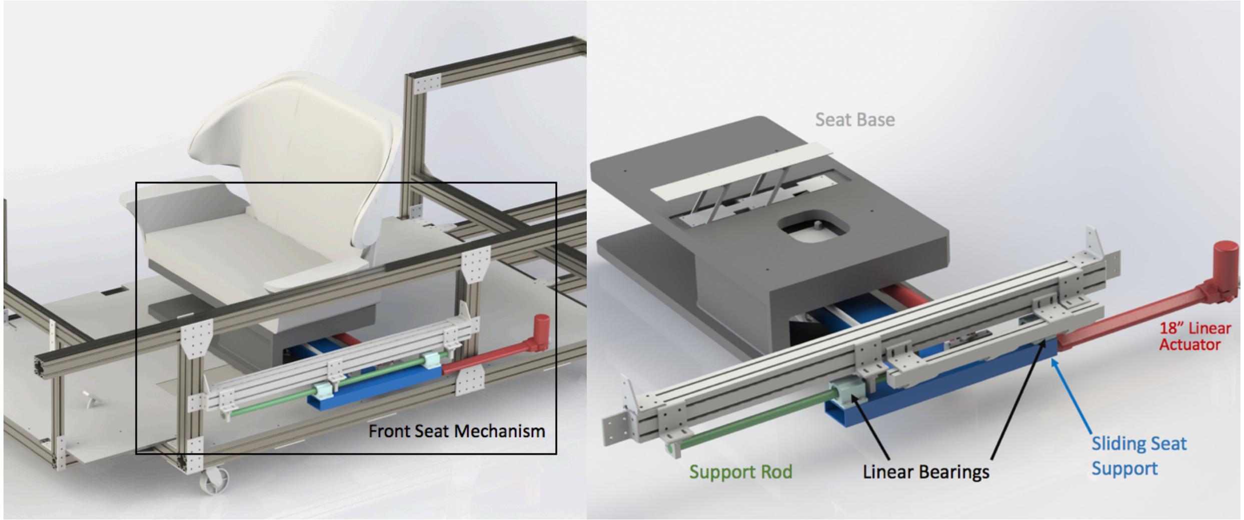


Figure 28: Front Seat Mechanism

The rear view provided by Figure 29 shows how the seat base is cantilevered over the floor in order to achieved the aesthetic design goal. Care was taken to ensure that the seat base, turntable, and sliding seat support could withstand sitting passengers and the weight of the seat itself. The load requirement was conservatively set to 600lb to accommodate two 225lb passengers and a total seat weight of 150lb.

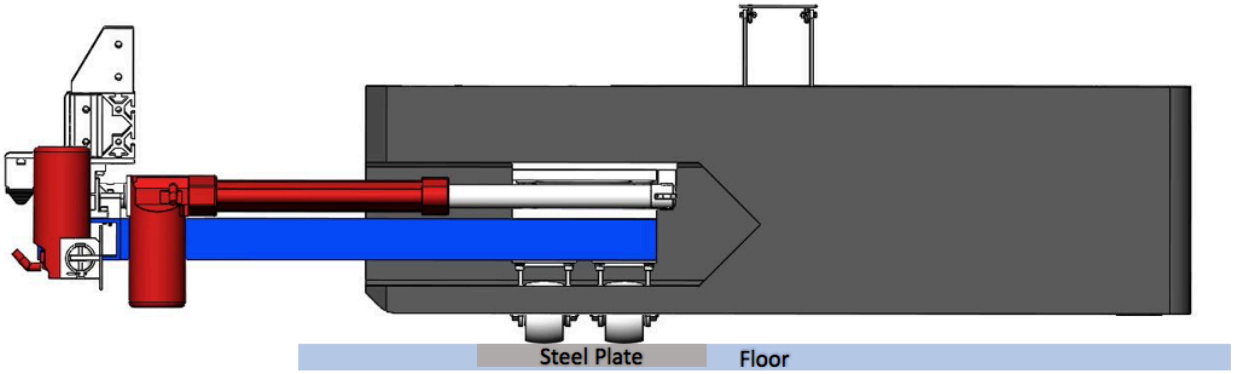


Figure 29: Front Seat Mechanism, Rear View

Given the 9.3” offset from the seat base center to the turntable location, the moment on the turntable at maximum load was approximated to be 9.3in x 600lb = 5580 in-lb. A 7500lb capacity turntable with a maximum offset load of 30,000 in-lb was selected. This application was well within the capabilities of the selected part, as the estimated maximum moment was only 17 percent the maximum capacity. This was important to minimalize deformation.

As a technology showcase, the seat base was to be 3d printed. A Big Area Additive Manufacturing (BAAM) 3D printer using Electrafil J-1200/CF20, an ABS with 20% carbon fiber fill, was selected. The 3D printer had a 12’ x 5.5’ x 6’ build envelope, and the carbon fiber filled ABS had higher stiffness and strength than alternative printable plastics while retaining good impact strength.

Table 6: Electrafil J-1200/CF20 Material Properties

Mechanical Properties	Unit	Test Method	Typical Property
Tensile Strength	psi	ASTM D638	13,000
Tensile Modulus	psi	ASTM D638	1,800,000
Tensile Elongation	%	ASTM D638	1.8
Flexural Strength	psi	ASTM D638	10,800
Flexural Modulus	psi	ASTM D638	1,740,00

With the help of CDME, a seat base capable of supporting the passengers was designed such that it could be printed without support material. Due to the 80 percent plastic build, the seat base could not be directly bolted to the turntable. Instead, a 34mm thick section of the seat base was sandwiched between two 9mm (3/8”) thick 177mm x 177mm plates of steel, shown in red in Figure 30. Four ½” bolts ran through seat base, both steel plates, and the turntable to hold the assembly together. The plates of steel helped to distribute this compression force over a large area of the seat base. The design called for machining of the contact surfaces of the seat base, post printing, to guarantee dimensional accuracy. The top surface and side edges of the seat base were also to be machined post printing for a better surface finish than the BAAM was capable of.

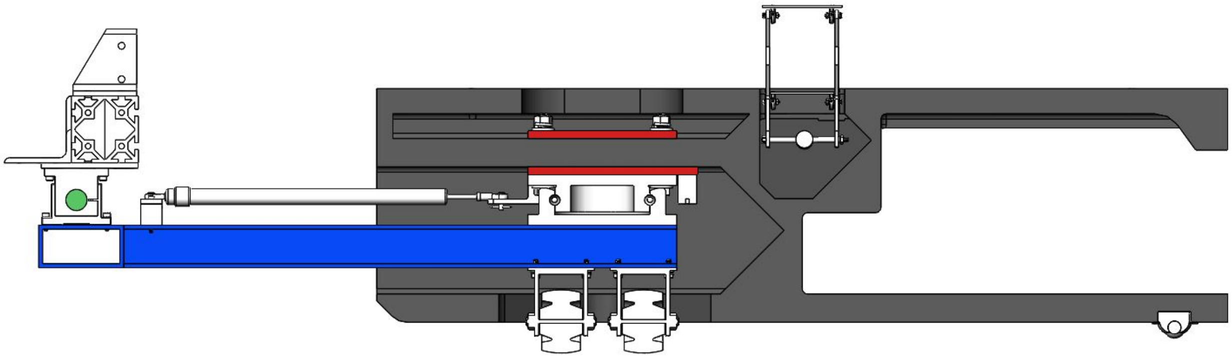


Figure 30: Front Seat Mechanism, Rear Section View

Finite element analysis was used to verify the strength of the seat base. The analysis performed was simplified, but was considered adequate for the purposes of this project given the goals and time constraints. A fixed constraint was applied to the areas of contact made by the two steel plates, and the 600lb force was applied uniformly to the top face of the seat base. The maximum stress was found to be 1,478 psi, well under the 13,000 psi tensile strength of the material. Figure 31 shows the results of this analysis. The design was also verified by Additive Engineering Solutions, as the additive manufacturing process can sometimes result in lower strength than a part assumed to be solid.

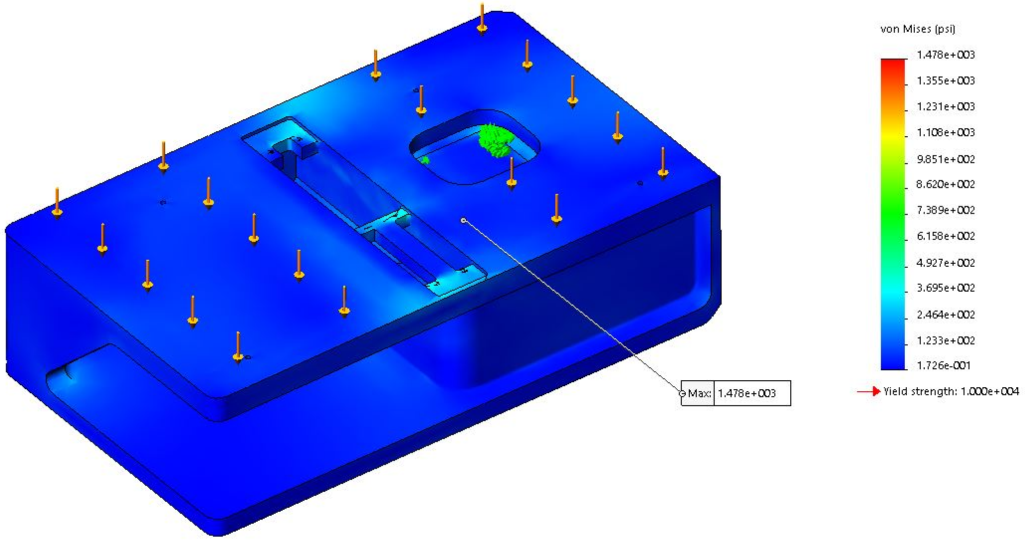


Figure 31: Front Seat, Stress Under Load

The deflection of the seat base was also checked to ensure that the seat did not contact the vehicle floor when loaded. The seat base height when unloaded was 35mm. The maximum deflection under the same conditions described in the stress test was found to be less than one millimeter, so deflection was not a concern. This result is shown in Figure 32.

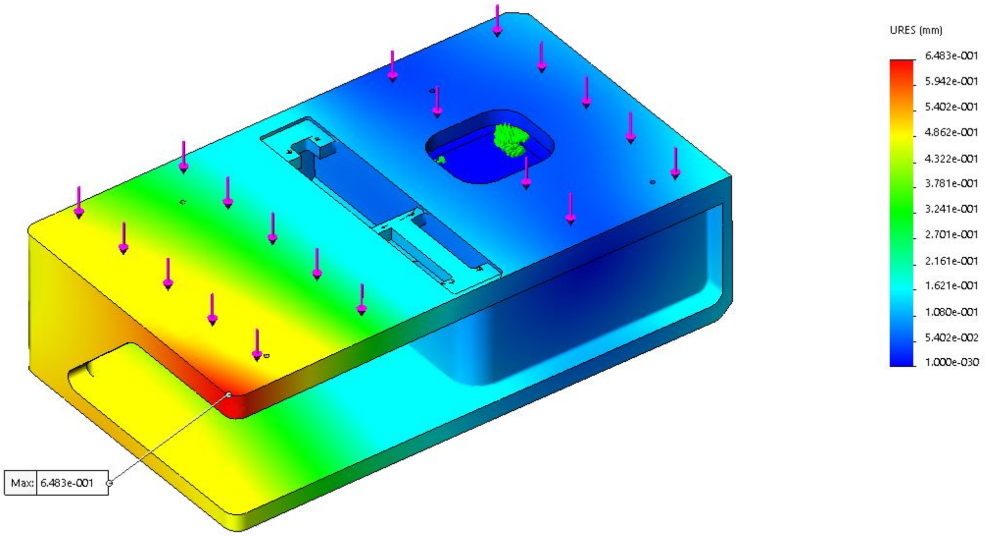


Figure 32: Front Seat, Deflection Under Load

Finally, the sliding seat support was designed. One 50.8mm x 101.6mm (2"x4") and one 60.8mm x 152.4mm (2"x6") rectangular steel beam were welded together, and the bottom of the turntable was welded to the end of the larger beam. Figure 33 shows the resulting piece. A wall thickness of 4.76mm (3/16") was selected. To verify the design, a simulation was run with 600lb force and 5580 in-lb moment applied to the turntable bottom. A fixed constraint was applied at the linear bearing bolt hold locations, and a roller constraint was applied on the face bolted to the caster wheels. To simulate full penetration welds, a bonded type contact was used to join the two steel beams and the turntable bottom. The maximum stress seen in this simulation was 26,840 psi—sufficiently under the 75,000 psi listed yield strength of the 4130 alloy steel tubes selected for the sliding seat support. Deflection of the turntable bottom was also verified to be minimal.

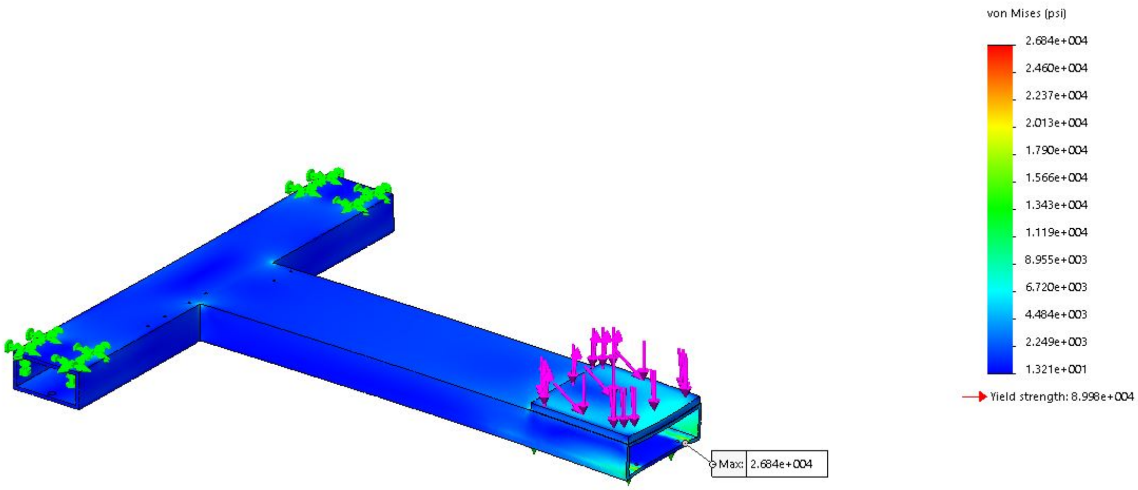


Figure 33: Sliding Seat Support, Stress Under Load

With the structural pieces of the front seat mechanism complete, actuators were selected to drive the motion of the seat base, starting with the actuator for the linear motion. It was assumed the linear motion and rotation would run in parallel while changing seat positions. The exact forward-facing seat position was not known at the time of actuator selection, because it was not yet known what rearward position would be most comfortable for the presentation practice scenario. The 18” full-rearward linear position was assumed as a conservative estimate. Given this assumption, the desired speed of the 18” linear actuator driving the linear motion of the mechanism was 2 in/sec.

Table 7: Required Speeds for Front Seat Mechanism

Mechanism Motion	Speed Target (seconds)	Linear Travel (inches)	Linear Speed Required (in/sec)	Rotation (degrees)
Front Seat: Entry to Forward-Facing and Forward-Facing to Entry	4	Max: 18-10 =8	2	45
Front Seat: Forward-Facing to Social and Social to Forward Facing	7	max 18-6 =12	1.71	90

An 18” stroke PA-04 Linear Actuator from Progressive Automation was selected, capable of 100 lb force and 2.8 in/sec unloaded and 2.16 in/sec under full load. The force capabilities were considered to be sufficient based on CDME’s recommendation, and the desired velocity target was meet even under full loading. An 18” 5K Ohm linear transducer was paired with this actuator for position feedback. Both actuator and linear transducer were pinned to the sliding seat support on one side and mounted using adjustable brackets to the extruded aluminum prototype frame on the other side.

For rotation, the 90-degree travel requirement was achievable using a linear actuator. This was preferable to a rotary actuator, which would need to be integrated into the turntable or require a chain or belt for power transmission. Figure 34 shows how the actuator was coupled to the seat base, with (A) showing the forward-facing position and (B) showing the social mode position.

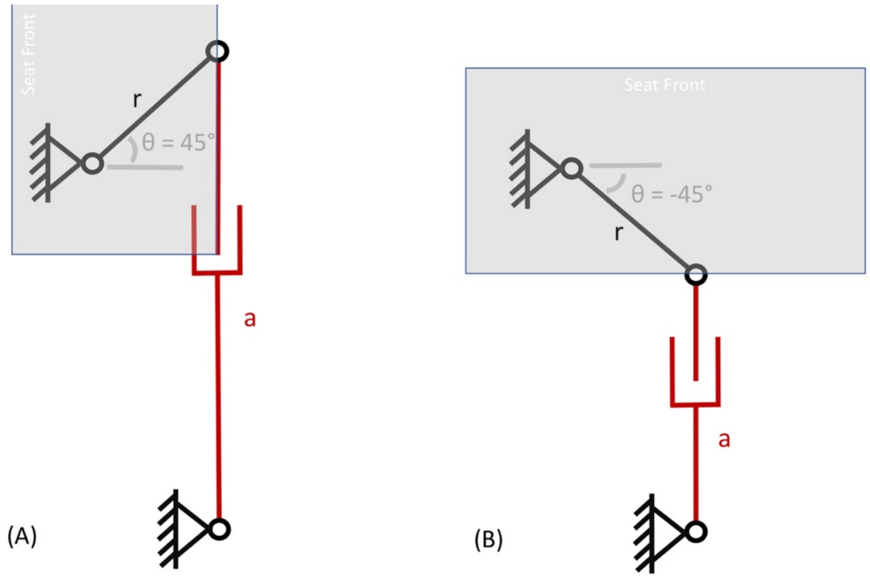


Figure 34: Front Seat Rotation Geometry, Top View

Commonality between all front and rear seat actuators was desired for easier control, so a PA-04 Linear Actuator was selected. A large offset between the actuator attachment location and axis of rotation, shown as r in Figure 34, would increase the moment applied by the actuator to the seat base and decrease rotational backlash. However, the larger the offset, the more visible the actuator. A compromise of r = 152.4mm (6in) was chosen, which kept the actuator far enough under the seat base to meet aesthetic requirements but allowed the 100lb actuator to provide cos(45)*6in*100lb = 424.2 in-lb of torque to the seat base at either end of the travel. More torque was available during the middle of the seat's rotation where the mechanical advantage was greater. This was considered to be sufficient based on CDME's recommendation and the low friction of the turntable.

Given the offset value, an actuator with sin(45)*6in*2 = 8.48 in of travel was required. The 10” version of the PA-04 actuator was selected. With 8.48 of travel distance, the speed requirement for the linear actuator was only 1.2 in/sec in order to meet the 7 second time requirement, which was met by the PA-04 actuator. A 250mm 10K Ohm linear transducer was paired with the actuator for position feedback on the opposing side of the turntable. The turntable plate was modified to provide mounting locations for the actuator and potentiometer, and mounting brackets were bolted to the sliding seat support. To reduce rotational backlash, the actuator ends were modified to accept press fit brass bushings, which allowed for tighter fitting pins.

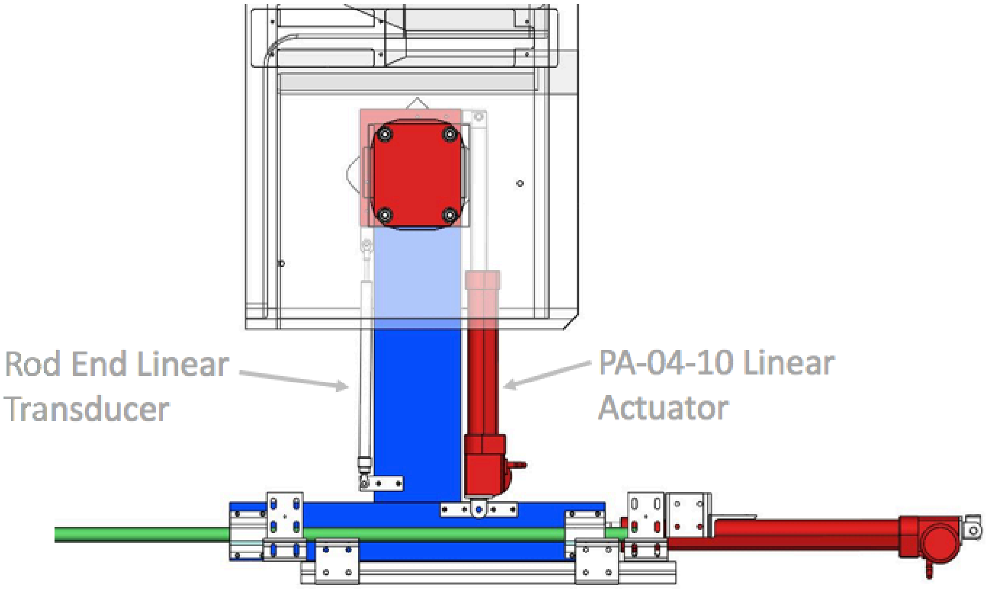


Figure 35: Front Seat Mechanism, Top View

5.4 Armrest Mechanism

The goal for the armrest mechanism was to allow the front seat to be configured like a couch, or be divided into something resembling more traditional seating. The armrest was split into two pieces: the mechanism and the upholstered pad. The aesthetic direction required the mechanism be hidden, and only the upholster pad be visible. The seat padding was 101.6mm (4”) thick, thus the target height of the armrest when deployed was to be close to, but not above, this 101.6mm height, so that the mechanism did not extend up above the seat padding. While deployed, the armrest was to extend forward as well, to better match the style of the fixed armrests on the left and right side of the chair. In the retracted position, the target height for the armrest mechanism was to be flush with the top surface of the seat base. This would allow the armrest pad and seat padding to be equal thicknesses—simplifying the upholstery requests.

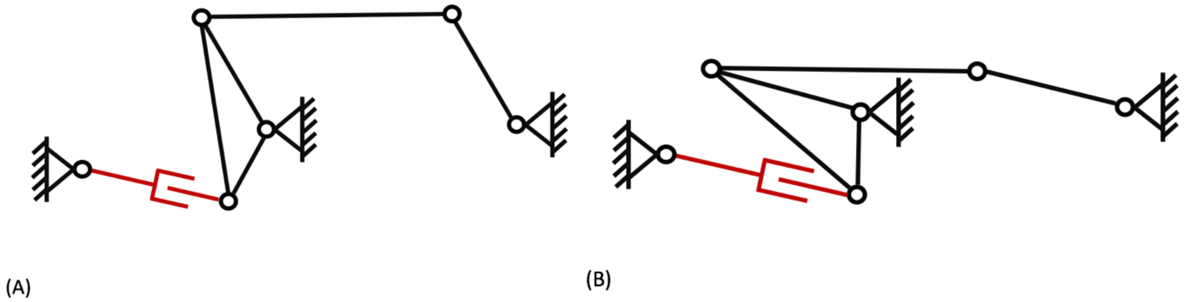


Figure 36: Preliminary Armrest Mechanism, Side View

Due to the turntable, constraints caused by 3D printing the seat base without supporting material, and space reserved for wiring of the front seat lighting, the mechanism had to be packaged within a small pocket in the front seat base. A four-bar linkage was designed to lift the armrest up by 89mm and forward by 45mm when deployed. Figure 36 shows the motion of this linkage. Figure 37 shows how this was packaged into the seat base. The linkage design shown in Figure 37 was provided to CDME for refinement and construction. The linkages were water-jet cut from 3/16" aluminum sheet. No analysis was done prior to construction, as the armrest was not included in the final user experience and intended only for a visual demonstration.

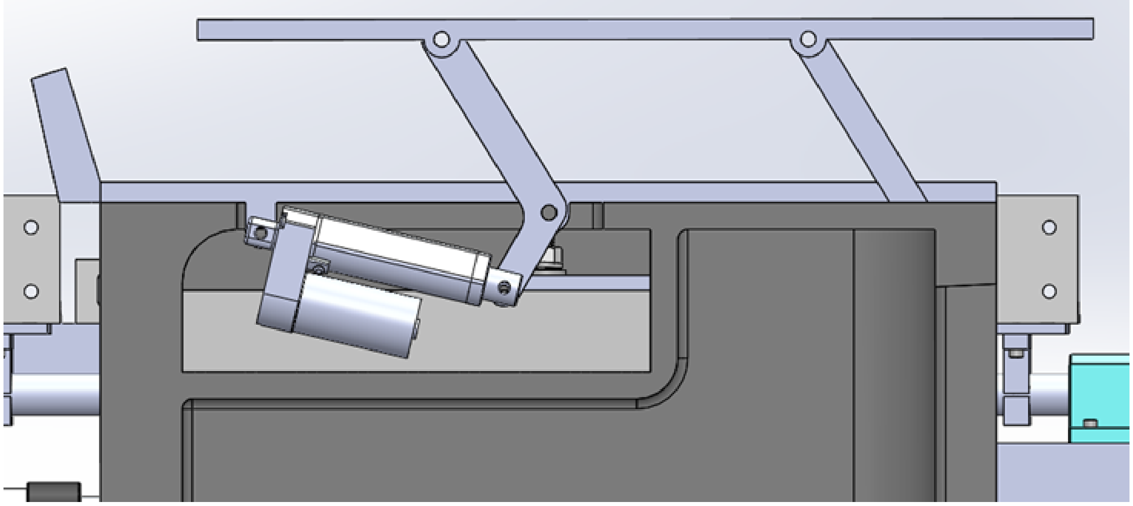


Figure 37: Preliminary Armrest Mechanism, Side View

A PA-14-2-50 Mini Actuator from Progressive Automation was selected with a 2" stroke, 50lb force, and a speed of 1.14 in/sec. This fit the 3 second speed requirement set for the armrest motion. The lever arm attached to the actuator was adjusted in length until the desired travel was achieved. As only the extremes of the motion would be demonstrated, and because the actuator had built-in limit switches, nothing additional was needed for positon feedback.

5.5 Mechanism Integration and Mockup Interior Construction

The integration of the discussed mechanisms within the aesthetic design of the vehicle was critical to the success of the APEX project. The engineering assemblies shown in this thesis had to be covered with painted and upholstered detailing in order to achieve an acceptable appearance. This section will show progress images, as well as the final interior, in order to provide context for the mechanisms covered in this chapter.

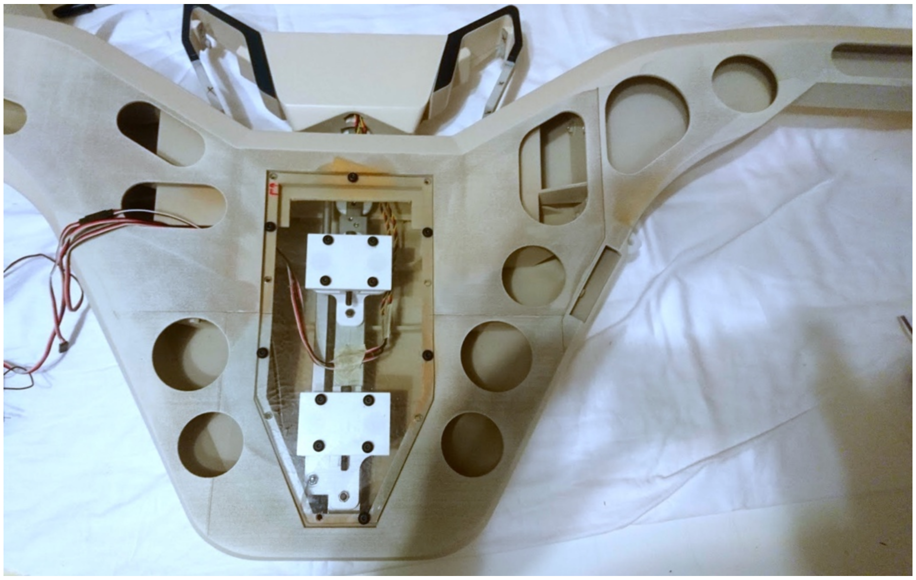


Figure 38: Steering and Dash Assembly, Bottom View

Figure 38 shows an underside view of the dash during construction. All fasteners attaching the steering mechanism described in Section 5.1 to the dash were on the underside, in order to maintain a smooth top surface. The dash was made up of three SLS nylon 3D prints, and was professionally painted by Honda Research America. Clearance between the steering wheel and dash was less than 1mm, which ensured a tightly integrated appearance when folded.

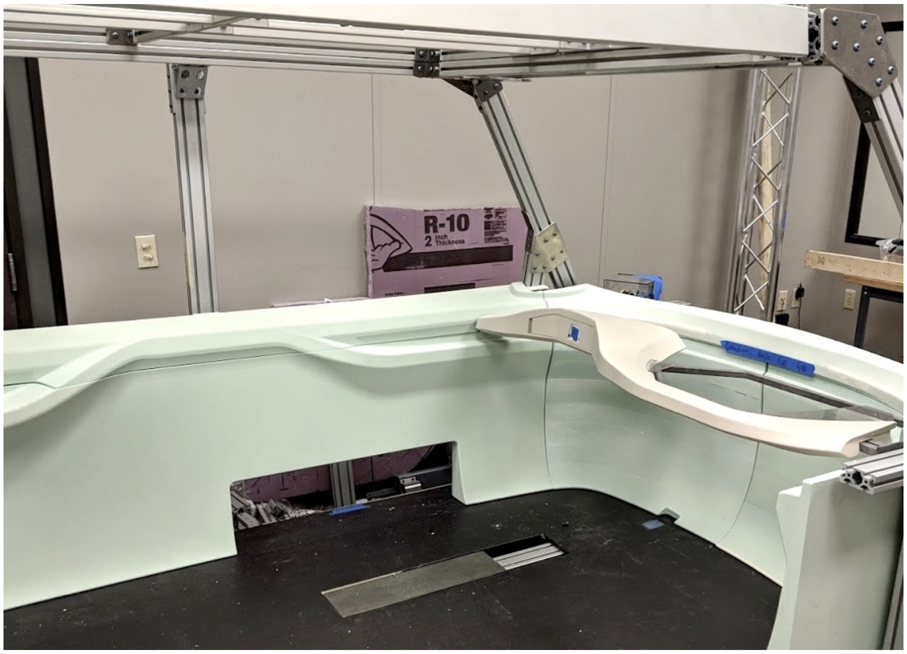


Figure 39: Steering and Dash Installation

Figure 39 shows the dash after installation. The steel plate for the front seat casters can also be seen in the floor. The body panels, which were CNC machined from urethane foam, are being test-fit to check clearance with the dash. Figure 40 shows the sliding seat support before instillation.

Figure 40: Sliding Seat Support Construction

Figure 41: Steering and Dash Installation

Figure 41 shows the interior after instillation of the sliding seat support and seat base. The armrest mechanism can be seen. Figure 42 shows the folding armrest motion after the rest of the front seat was complete. Lighting elements on the front seat—the electronics of which were packed alongside the armrest mechanism—can also be seen.

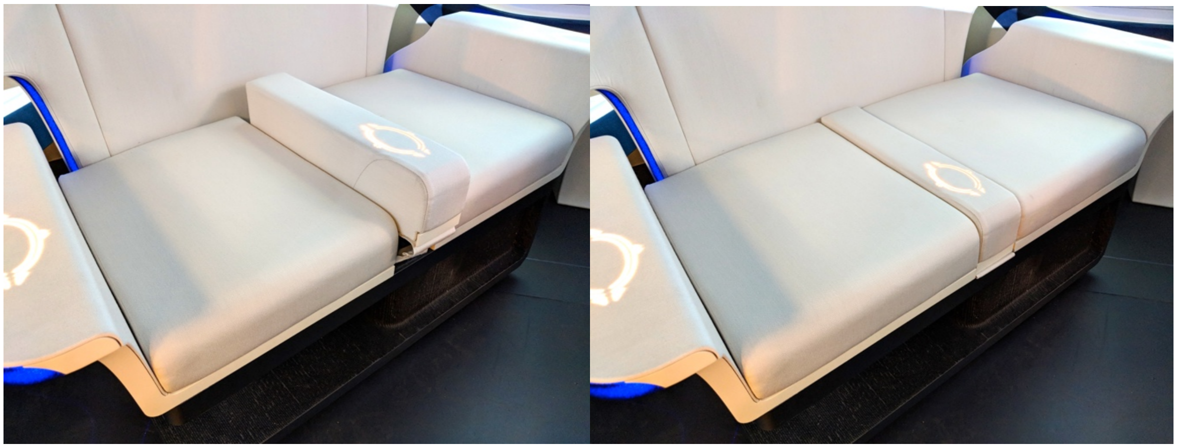


Figure 42: Complete Moving Armrest

Finally, the complete interior can be seeing in Figures 43 and 44. Figure 43 shows the entry position of the front seat, where the front seat is angled 45 degrees. Figure 44 provides two interior views: (A) shows the view of a single passenger with the steering wheel folded, and (B) shows the seating in multi-user configuration.

Figure 43: Complete Interior Mockup, Entry Position

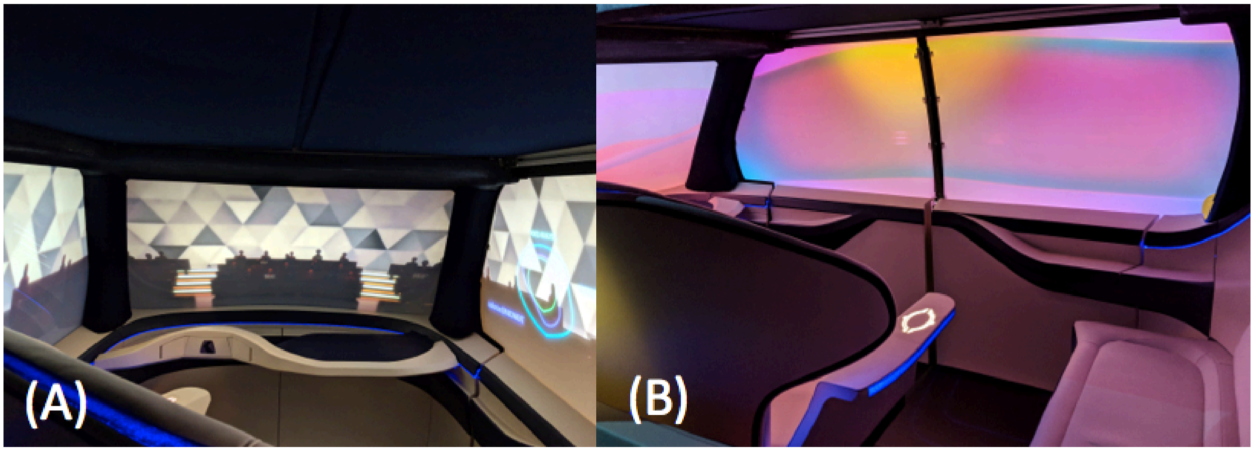


Figure 44: Complete Interior Mockup, Interior Views

Chapter 6: Control Software, Electronics, and Verification

This chapter will cover the software and electronics used in the control of the folding steering wheel, folding pedal, and moving seats. For safety reasons, the desired mode for each moving part was selected manually from behind the mockup, instead of by users experiencing the mockup. The electronics for the steering wheel and pedal was independent of the electronics used for the moving seats.

6.1 Steering and Pedal

The items that needed controlled for the reconfigurable steering and pedal can be seen in Table 8. An Arduino Uno microcontroller was selected, as it had the required 4 PWM output and was simple to program in the available time.

Table 8: Required Control, Steering and Pedal

Actuator	Voltage	Control	Feedback
50:1 L12-R micro linear servo- Pedal	4.8V - 6.0V	PWM	n/a
Hi-Tec HS-805BB Servo - Left Handle	4.8V - 6.0V	PWM	n/a
Hi-Tec HS-805BB Servo - Right Handle	4.8V - 6.0V	PWM	n/a
50:1 L12-R micro linear servo - Steering	4.8V - 6.0V	PWM	n/a

Figure 45 shows how the four servos were connected to the Arduino Uno. Instead of using the Arduino for power, a 12v to 6v DC DC converter was used to power the servos. This helped to avoid brownout problems that can be caused when a servo draws too much power from an Arduino, and ensured maximum servo speed. While idle, the servos emitted noise that was undesirable for the prototype, so a relay was used to control the power going to all four servos. This allowed the servo power to be disconnected when the servos were not in use, without deactivating the Arduino. A toggle switch wired to a digital input pin with a pull-down resister was used to select between extend and retract.

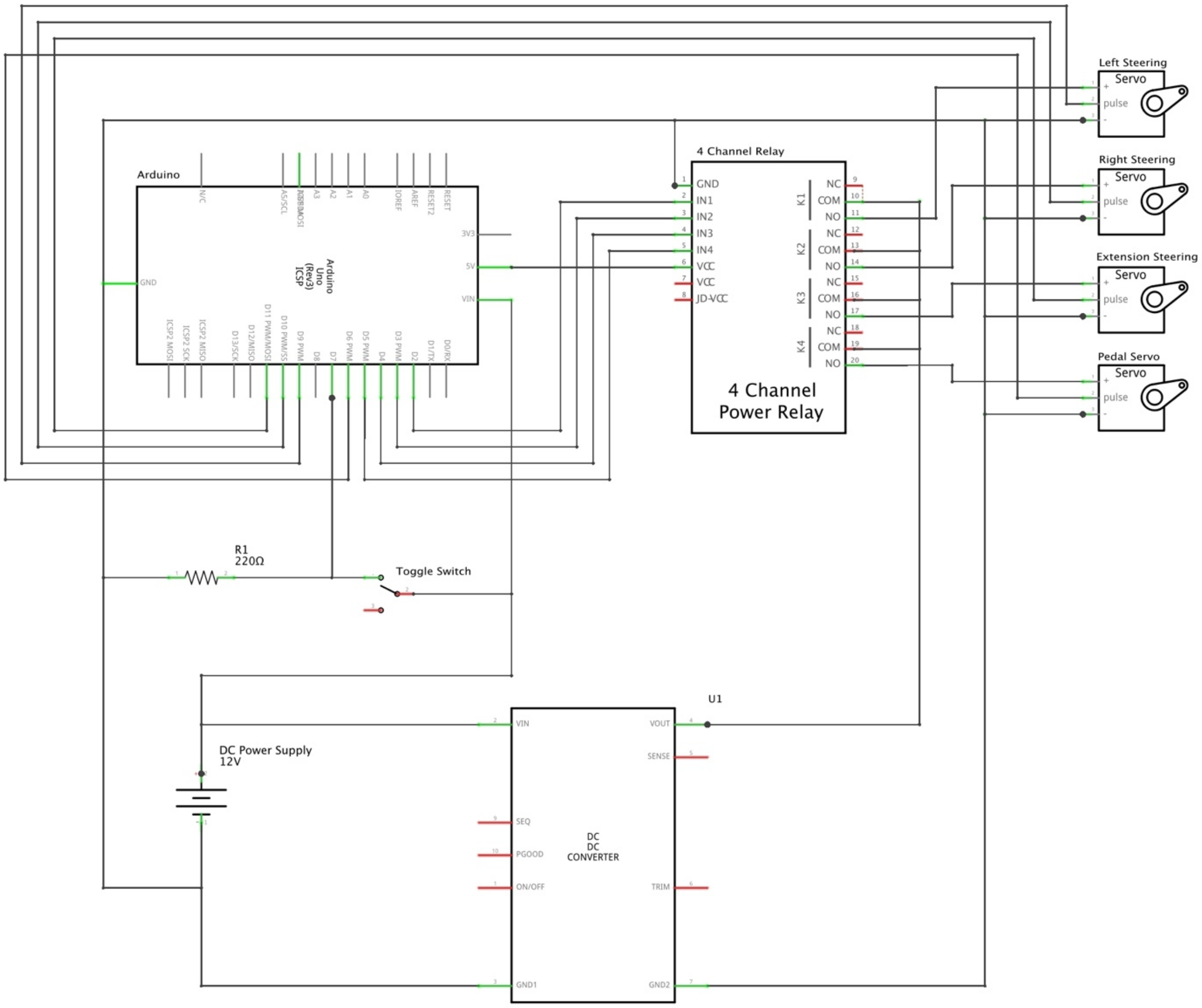


Figure 45: Steering and Pedal Control Schematic

Upon startup, the Arduino cycled through a startup procedure that reset the steering to the retract position. This procedure insured that the steering wheel handles did not catch on the dash, regardless of initial position. It also helped with identifying servo issues, as damage would occur if the handles were not folded during steering retraction. First, power was applied only to the steering linear actuator, and the actuator was extended.

Then power was applied to the handles, they were folded, and a 4 second delay occurred to provide time for a visual check of the handle position. This check helped verify the handle mounts and function of the handle servos. Finally, the linear actuator retracted and power to all servos was removed.

After this setup procedure, the program entered a main loop. Here, the steering and pedal were extended or retracted depending on the toggle switch position. A state variable kept track of the current position. Figure 46 shows simplified pseudocode for the code run within the main loop.

```
Read digital pin 7
if pin 7 = High and State = Low
        Extend wheel:
                Set relays to power pedal and steering lin. servo
                Set pedal position: extended, Set steering position: extended
                Wait 4.6 seconds
                Set relays to power handle servos
                For G = 0 to 87
                        Set left handle position to 169 – G
                        Set right handle position to 9 + G
                        Wait 34 ms
                End
                Set relays to remove power from all servos
        Set State = High
End
if reading = Low and State = High
        Retract wheel:
                Set relays to power pedal and steering lin. servo
                Set pedal position: extended, Set steering position: retract
                Set relays to power handle servos
                For G = 0 to 87
                        Set left handle position to 80 + G
                        Set right handle position to 96 - G
                        Wait 10 ms
                End
                Wait 5.13 seconds
                Set relays to remove power from all servos
        Set State = Low
End
```

Figure 46: Steering and Pedal Algorithm Pseudocode

Figure 47 shows the servo angle inputs over time for the steering wheel and pedal extension, and the full code can be seen in Appendix B. The Arduino servo library, with the default PWM frequency range of 544 to 2400 μs, was used for control. There was no appropriate library for the linear servos, but this proved not to be an issue as exact position control was not needed for the steering extension or pedal extension. The standard servo library was used, and the input angle for the standard Arduino servo library for full-extend and full-retract was manually found to be 145 and 40, respectively.

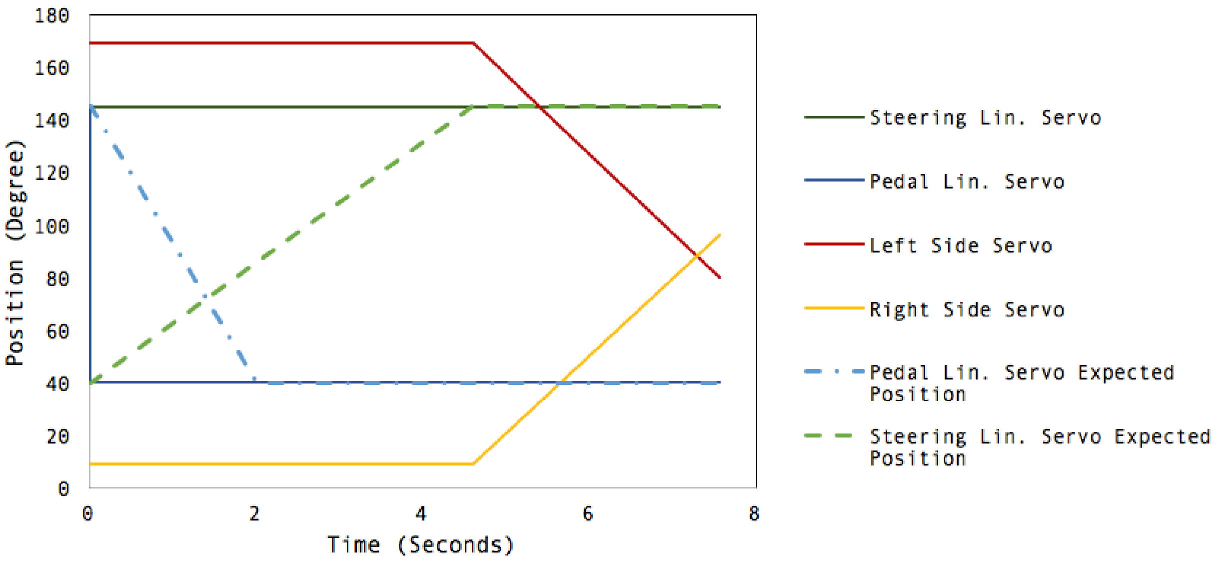


Figure 47: Extending Steering and Pedal Control

Given this process, the expected total time for the steering extension was 7.55 seconds. The handles unfolded at a rate of 29.4 degrees/second, which provided a smooth reveal of the steering wheel. A quicker drama-free retraction was desired, and the handles were commanded to move at a rate of 69.8 degrees/second durring folding. The expected total retraction time was 6 seconds. Retraction process is shown in Figure 48.

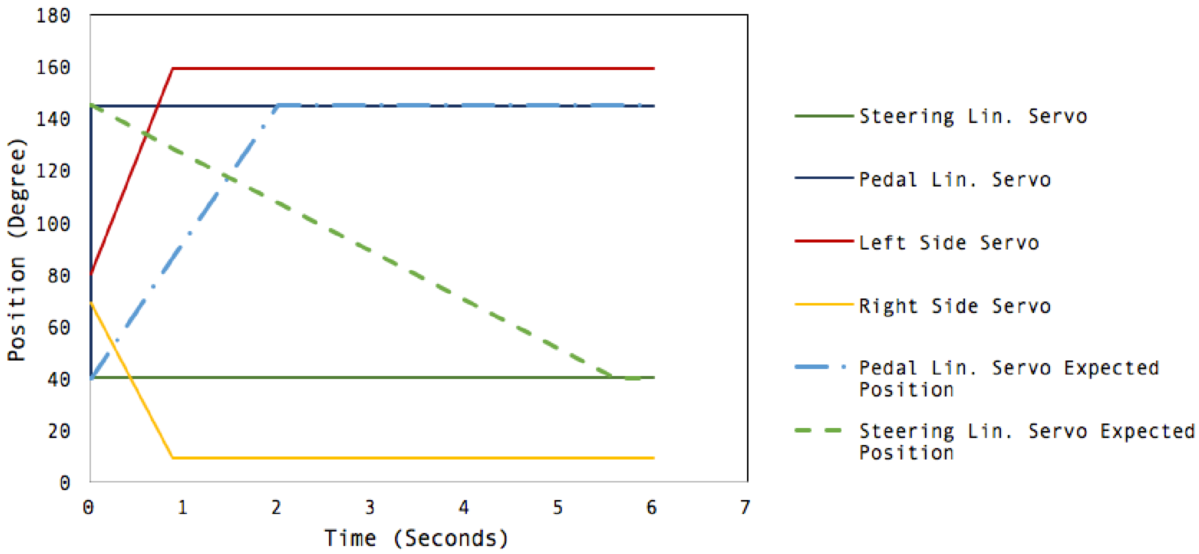


Figure 48: Retracting Steering and Pedal Control

5.2 Seating and Roof

Table 9 shows the control requirements for the seating and roof. An Arduino Mega was used. Robot Power Simple-H H bridges capable of 45A peak current were used for motor control. A 600 Watt benchtop power supply from B&K Precision was used.

Table 9: Required Control, Seating and Roof

Actuator	Voltage	Max Current	Control	Feedback
Roof Linear Actuator (x2)	12V	28A	PWM	n/a
Lin. Actuator – Front Seat Lin. Motion	12V	12A	PWM	n/a
Lin. Actuator – Front Seat Lin. Motion	12V	12A	PWM	10 kΩ lin transducer
Lin. Actuator – Front Seat Rotation	12V	12V	PWM	5 kΩ lin transducer

The wiring diagram for the seating and roof can be seen in Figure 49. Each simple H bridge was connected to two PWM pins, with one PWM input controlling the forward direction, and the second controlling reverse.

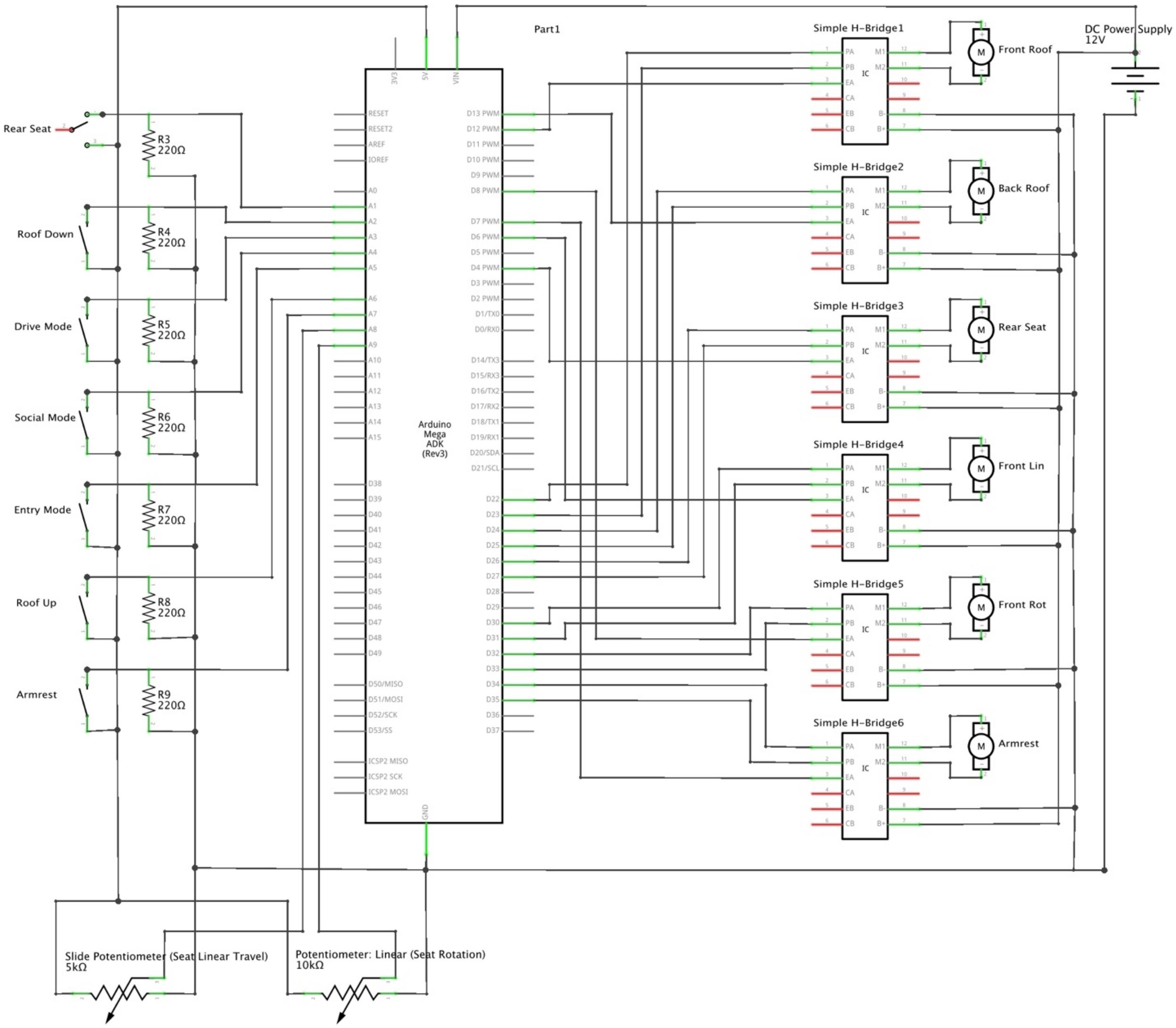


Figure 49: Retracting Steering and Pedal Control

One toggle switch was wired with a pull-down resister to control rear seat position. Six momentary buttons were added with pull-down resisters to toggle armrest position, front seat position, and control roof motion.

Simplified pseudocode for the main loop of the seat and roof control can be seen in Figure 50, and the full code can be seen in Appendix C. For the armrest and rear seat, the built in actuator limit switches were used for position control, and constant speed was used for the motion. Linear acceleration and deceleration was used for the motion of the front seat.

```
Read digital pin A1, A6, A7
if pin A1 = High: Set Rear Seat Actuator to Extend
if pin A1 = Low: Set Rear Seat Actuator to Retract
if pin A6 = High: Set Roof Actuators to Extend
if pin A6 = Low: Set Roof Actuators to Break
if pin A7 = High: Set Roof Actuators to Extend
if pin A7 = Low: Set Roof Actuators to Break

Read digital pin A7
if pin A1 = High and Armrest State = Low
        Set Rear Seat Actuator to Extend
        Set Armrest State = High
End
if pin A1 = High and State = High
        Set Rear Seat Actuator to Retract
        Set Armrest State = Low
End

Linear Traveled = Linear potentiometer reading – Linear potentiometer reading @ zero
Rot. Traveled = Rotation potentiometer reading – Rotation potentiometer reading @ zero

(Ramp Speeds up)
L actuator speed unconstrained = Linear Traveled * (MaxL - MinL)/(Max Lin. Travel* .25)
L actuator speed = Constrain (L actuator speed unconstrained, MinL, MaxL)
R actuator speed unconstrained = Rot. Traveled * (MaxR - MinR)/(Max Rot. Travel* .4)
R actuator speed = Constrain (R actuator speed unconstrained, MinR, MaxR)

(Ramp Speed Down)
If Linear Traveled > Travel L Max * .6
        L actuator speed unconstrained = (Linear Traveled– Max Lin. Travel)*(MaxL- MinL)/(Max Lin. Travel *.4)
        L actuator speed = Constrain (linear speed unconstrained, Min, Max)
end
If Rotational Traveled > Travel R Max * .6
        Rot Speed unconstrained = (Rot. Traveled – Max Rot. Travel *.6)*(MaxR-MinR)/(Max Rot. Travel *.4)
        R actuator speed = Constrain (R actuator speed unconstrained, MinR, MaxR)
end

If pin A3 = High: Set Actuator Directions for Forward-Facing Mode
If pin A4 = High: Set Actuator Directions for Social Mode
If Pin A5 = High: Set Actuator Directions for Entry Mode
```

Figure 50: Front seat, Rear Seat, etracting Steering and Pedal Control

During the initial 40% of the rational motion and 25% of the linear motion, velocity ramp up occurred. After this point, the velocity was bound using the “Constrain” function by MaxL or MaxR, the maximum allowed actuator speed. During the final 40% of travel, deceleration occurred.

Simplified pseudocode for the process of setting actuator direction, mentioned but not shown in Figure 50, can be seen in Figure 51. Setting the actuator direction for forward-facing mode is shown, but the other seat positions all follow the same algorithm.

```
If pin A3 = High and Seat State = 0
    Set Linear potentiometer reading @ zero to current value
    Max Lin. Travel = L Driving Position – Linear potentiometer reading @ 0
    Seat State = 1
End
If Seat State = 1
    If Linear potentiometer reading > L Driving Position: Set Lin. Seat Actuator to Retract
    If Linear potentiometer reading < L Driving Position: Set Lin. Seat Actuator to Extend
    Else
        Set Lin. Seat Actuator to Break
        Linear State = 1
    end

    If Rot. potentiometer reading > R Driving Position: Set Rot. Seat Actuator to CW
    If Rot. potentiometer reading < R Driving Position: Set Rot. Seat Actuator to CCW
    Else
        Set Rot. Seat Actuator to Break
        Rotational State = 1
    end
    If Linear State = 1 and Rotational State = 1
        Linear State = 0
        Rotational State = 0
        Seat State = 0
        Current Drive Mode = 1
End
```

Figure 51: Seat Actuator Directions, Forward-Facing Mode

5.3 Software Verification

The steering electronics and software was tested successfully, and the folding process occurred as expected without any significant deviation in expected extension and retraction time. The folding pedal also worked as expected.

The front seat motion, however, required tuning. The minimum actuator speed at the beginning and end of the actuator travel, for both linear and rotational, produced a high pitch noise. Additionally, the velocity ramp-down for the rotational motion was too aggressive and the seat would not reliably reach the final rotational position. The speed at the start of the initial ramp and end of retraction had to be increased significantly in order to reduce the noise and increase reliability. The result was a reliable motion, but one with a very gradual velocity ramp and a high start and end velocity. Given the project timeline, a more intelligent control algorithm was not attempted—although any other control method would have likely encountered the same noise issue at low velocities.

The greater start and end velocity was acceptable for passengers when moving between forward-facing mode and social mode. However, moving between the entry and forward-facing positions was too abrupt and required adjustment. The linear position of entry mode was adjusted to match the linear position of the forward-facing mode. Removing the linear motion resulted in a much smoother transition, and the position change was minor enough not to significantly impact the entry position.

As described in Appendix A, the choreographed user experience required transition from entry to forward-facing, then to social mode, then forward-facing, and finally back to entry. The final potentiometer output for the front seat during this process can be seen in Figure 52 through 55.

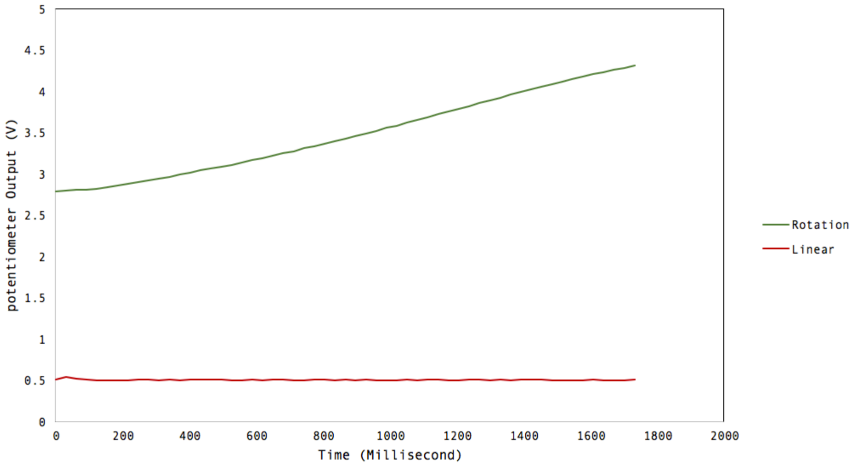


Figure 52: Front Seat Motion, Entry to Forward-Facing Position

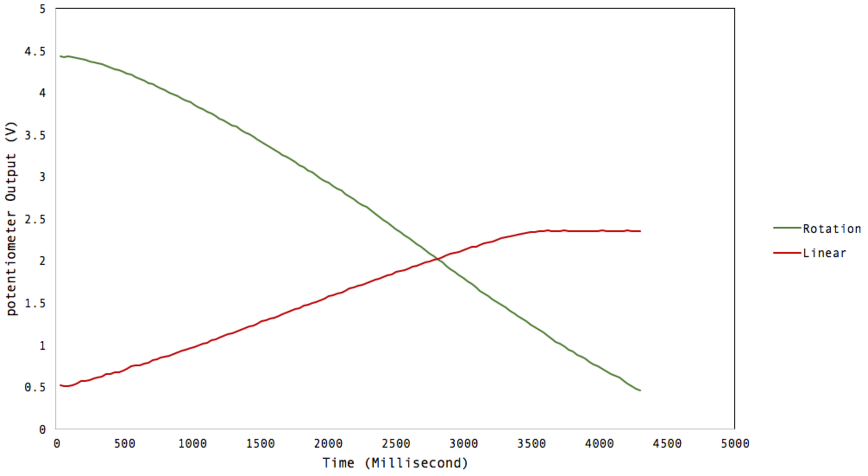


Figure 53: Front Seat Motion, Forward-Facing Position to Social Mode

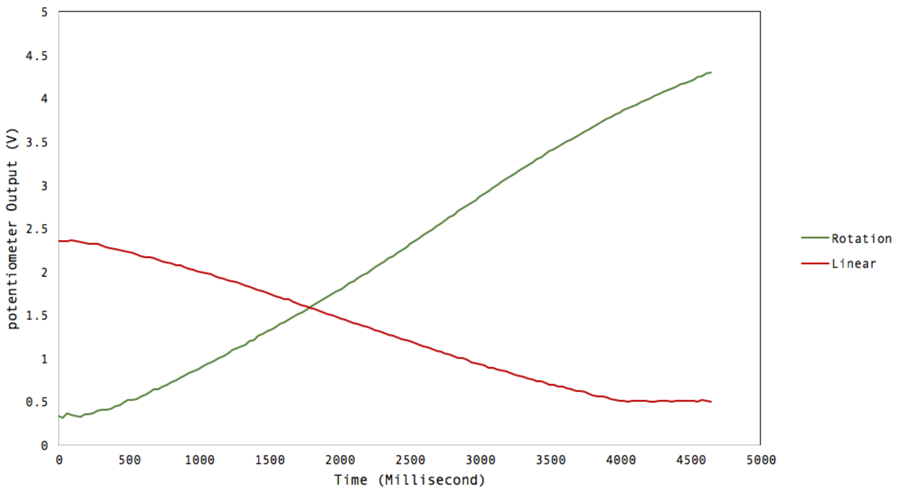


Figure 54: Front Seat Motion, Social Mode to Forward-Facing Position

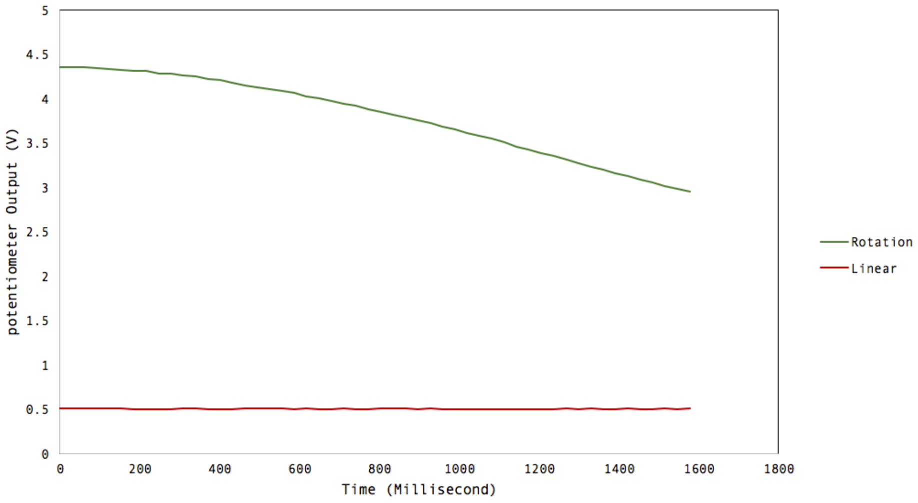


Figure 55: Front Seat Motion, Forward-Facing Position to Entry

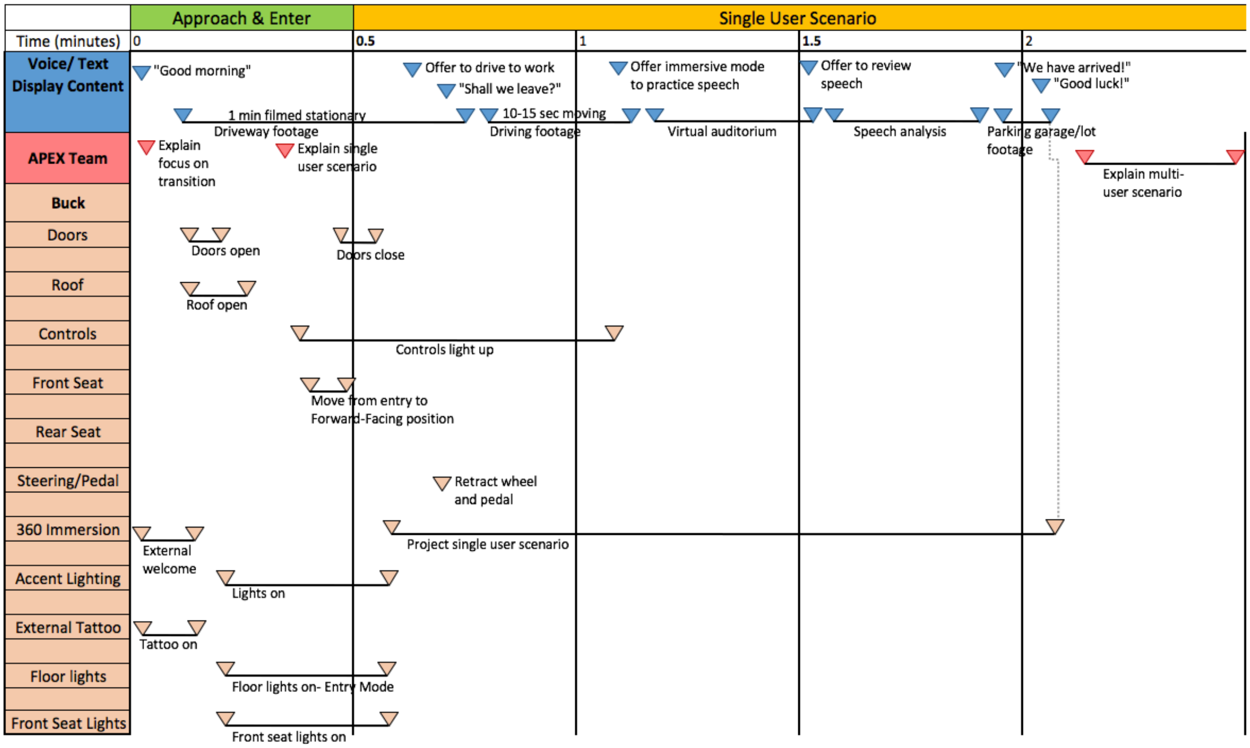
Chapter 7: Conclusions

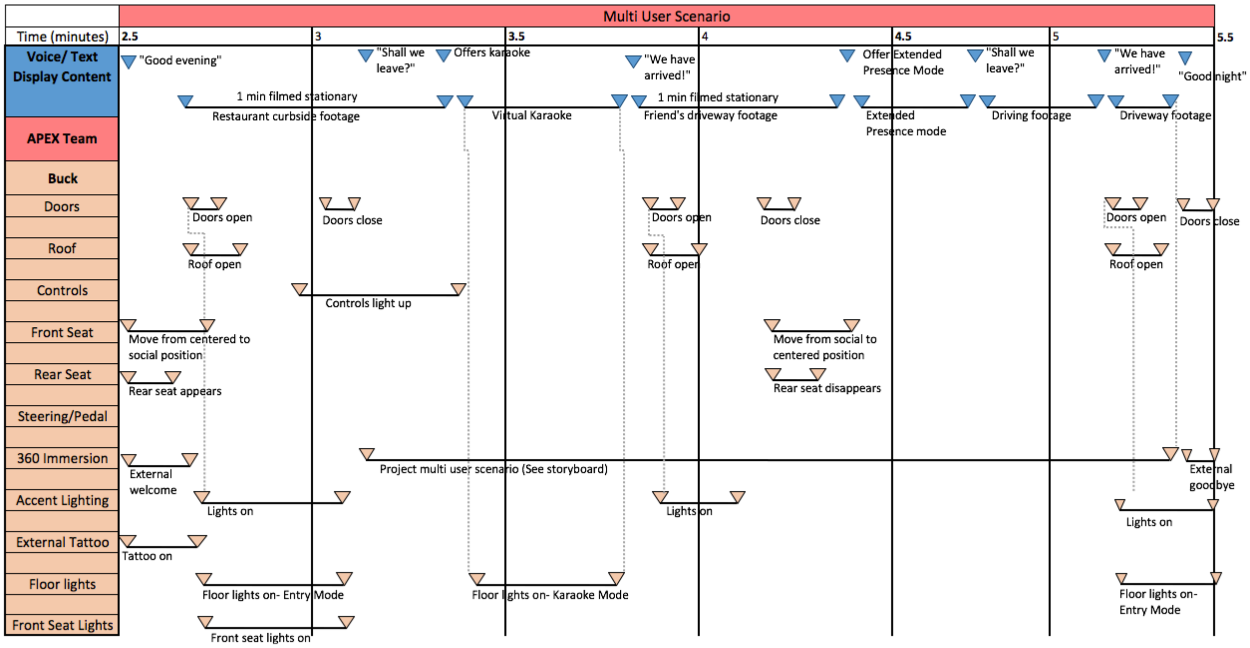
We are in the initial stages of vehicle autonomy, and the future is still unknown. APEX 01 was an exploration of what the future may hold. The interior that has been designed and constructed addresses the new constraints and freedoms that may be provided by autonomy, and provides a launching point for additional user experience and technology research.

The full-scale mockup of the reconfigurable interior was successfully demonstrated to Honda executives. Timing of the presentation followed the timing that had been choreographed and can be seen in Appendix A.

Next, the user experiences showcased in APEX 01 will be evaluated by future students. They will perform user clinics and other research to see how potential users respond to the experiences proposed. The reconfigurable interior was critical for enabling some of the experiences that will be evaluated, such as the lounge-like social seating configuration and folding steering.

Appendix A: User Scenarios





Appendix B: Steering and Pedal Code

```
// Citation: [17]
#include <Servo.h>
Servo lefthand;// create servo object to control a servo
Servo righthand;
Servo extension;
Servo pedal;

int posL = 169;    // variable to store the servo positions
int posR = 9;
int G = 0;
int inPin = 7;         // the number of the input pin
int reading;           // the current reading from the input pin
int state = LOW;      // the current state is retracted

void setup() {
 lefthand.attach(9);      // attaches the servos on pin 6, 9-11 to the servo objects
 righthand.attach(10);
 extension.attach(11);
 pedal.attach(6);

 pinMode(inPin, INPUT);
 // initialize digital pin LED_BUILTIN as an output.
 pinMode(LED_BUILTIN, OUTPUT);

 pinMode(2, OUTPUT);         // sets the digital pins as outputs for relay
 pinMode(3, OUTPUT);         //pin 2,3 are handles, pin 4 is extension, pin 5 is pedal
 pinMode(4, OUTPUT);
 pinMode(5, OUTPUT);

   //Start with all power off. Pin high, servo off
    digitalWrite(2, HIGH);
    digitalWrite(3, HIGH);
    digitalWrite(4, HIGH);
    digitalWrite(5, HIGH);

   //Safety RUN: fold handles closed, and extend (to ensure handles are clear of opening)
    digitalWrite(4, LOW);
    extension.write(145);   //E: 145 is wheel extended
    delay(5700);

    digitalWrite(2, LOW);
    digitalWrite(3, LOW);
    lefthand.write(169);    //L: 169 and R: 9 is Wheel closed
    righthand.write(9);
```

```
   delay(4000);           //Delay for visual check that handles are folded
   digitalWrite(2, HIGH);
   digitalWrite(3, HIGH);

  //After this wheel state is known: retracted, servos off.
   extension.write(40);  //E: 40 is wheel retracted
   delay(8000);
   digitalWrite(4, HIGH);
}

void loop() {
 reading = digitalRead(inPin);
   if (reading == HIGH && state == LOW) {
         digitalWrite(LED_BUILTIN, LOW);// turn the LED off by making the voltage LOW
          //EXTEND Steering
            digitalWrite(4, LOW);
            digitalWrite(5, LOW);//pedal
            extension.write(145);   //E: 145 is wheel extended
            pedal.write(40); //pedal extended
            delay(4600);
         //OPEN WHEEL (posL 169->80 . PosR 9->96)
            digitalWrite(2, LOW);
            digitalWrite(3, LOW);
            for(G = 0; G<=87; G += 1){
             int posL = 169 - G;
             int posR = 9 + G;
             lefthand.write(posL);    //L: 80  R: 96 Wheel open
             righthand.write(posR);
             delay(34);
            }
            lefthand.write(80);    //L: 80  R: 96 Wheel open
            righthand.write(96);
            delay(2000);
            digitalWrite(4, HIGH);
            digitalWrite(5, HIGH);
            digitalWrite(2, HIGH);
            digitalWrite(3, HIGH);
            delay(2000);
            state = HIGH;
   }

   if (reading == LOW && state == HIGH) {
     digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on (HIGH is the voltage level
       //SET RETRACTION
          digitalWrite(4, LOW);
          digitalWrite(5, LOW);//pedal
          extension.write(40);  //E: 40 is wheel retracted
```

```
            pedal.write(145); //pedal extended
        //CLOSE WHEEL (posL 80->169 . PosR 96->9)
            digitalWrite(2, LOW);
            digitalWrite(3, LOW);
            for(G = 0; G<=87; G += 1){
              int posL = 80 + G;
              int posR = 96 - G;
              lefthand.write(posL);    //L: 80  R: 96 Wheel open
              righthand.write(posR);
              delay(10); //14
            }
            lefthand.write(169);    //L: 169 and R: 9 is Wheel closed
            righthand.write(9);
            delay(5130);
            digitalWrite(4, HIGH);
            digitalWrite(5, HIGH);
            digitalWrite(2, HIGH);
            digitalWrite(3, HIGH);
            delay(2000);
            state = LOW;
    }
}
```

Appendix C: Seat and Roof Code

```
// Citation: [18]
// BUTTON
const int Rear = A1;
//Button Inputs
const int Drive = A3;
const int Social = A4;
const int Entry = A5;
const int Arm = A7;

int Rear_Button;
int Arm_Button;
int Drive_Button;
int Social_Button;
int Entry_Button;

// H-BRIDGE MOTOR SETUP
const int L_E = 6; //Linear - H Bridge Enabler
const int L_MF = 30; //Motor output (forward), analog out
const int L_MB = 31; //Motor output (backward)
const int R_E = 8; //Rotation
const int R_MCW = 33;
const int R_MCCW = 32;
const int RS_E = 4;//Rear Seat
const int RS_MF = 26;
const int RS_MB = 27;
const int RR_E = 12; //Right Roof
const int RR_MO = 22;
const int RR_MC = 23;
const int RL_E = 13; //Left Roof
const int RL_MO = 24;
const int RL_MC = 25;
const int A_E = 7; //Armrest
const int A_MU = 35;
const int A_MD = 34;

// POTENTIOMETERS
const int R_P = A8; const int L_P = A9;

int PotRead_L = 0; int PotRead_L0 = 0; int PotRead_R = 0; int PotRead_R0 = 0;

int Travel_L; int Travel_L_Max; int Travel_R; int Travel_R_Max;

//Set Min and Max for each actuator
const int L_Social = 480;
```

```
const int R_Social = 45;
const int L_Driving = 92;
const int R_Driving = 930;
const int L_Entry = 92;
const int R_Entry = 575;

// Set Speed Min and Max for each actuator
int L_Speed_Min = 180;
int L_Speed_Max = 255;
int L_Speed = L_Speed_Min;

int R_Speed_Min = 185;
int R_Speed_Max = 255;
int R_Speed = R_Speed_Min;

int Roof_Speed = 255;
int Arm_Speed = 255;

// Declare Counters
int C1_Rear = 0; int C2_Rear = 0; int C_Rear;
int C1_Arm = 0; int C2_Arm = 0; int C_Arm;

// State Counters
int S_L = 0; // 0 = Disengaged, 1 = Engaged
int S_R = 0;
int S_Drive = 0;
int S_Social = 0;
int S_Entry = 0;
int S_Arm = 0;
int S_Rear = 0; // 0 = Closed, 1 = Open
int S_Doors = 0; // 0 = Closed, 1 = Open

int Front123 = 2; // Drive = 1, Social = 3

// Set Run Durration
const int Door_Run = 3000; //Door
const int Roof_Run = 5500; //Roof

const int Rear_Run = 7000; //Rear seat
const int Arm_Run = 3000; //Arm rest


// ----------------FUNCTIONS------------------------------------

// MOTOR MOVEMENT FUNCTIONS
void Arm_Up(){
  digitalWrite(A_E, LOW);
```

```
  digitalWrite(A_MU, HIGH);
  digitalWrite(A_MD, LOW);
  analogWrite(A_E, Arm_Speed);
}
void Arm_Down(){
  digitalWrite(A_E, LOW);
  digitalWrite(A_MU, LOW);
  digitalWrite(A_MD, HIGH);
  analogWrite(A_E, Arm_Speed);
}
void Arm_Brake(){
  digitalWrite(A_E, LOW);
  digitalWrite(A_MU, LOW);
  digitalWrite(A_MD, LOW);
  analogWrite(A_E, HIGH);
}
void L_Forward(){
  digitalWrite(L_E, LOW);
  digitalWrite(L_MF, HIGH);
  digitalWrite(L_MB, LOW);
  analogWrite(L_E, L_Speed);
}
void L_Backward(){
  digitalWrite(L_E, LOW);
  digitalWrite(L_MF, LOW);
  digitalWrite(L_MB, HIGH);
  analogWrite(L_E, L_Speed);
}
void L_Brake(){
  digitalWrite(L_E, LOW);
  digitalWrite(L_MF, LOW);
  digitalWrite(L_MB, LOW);
  analogWrite(L_E, HIGH);
}
void R_CW(){
  digitalWrite(R_E, LOW);
  digitalWrite(R_MCW, HIGH);
  digitalWrite(R_MCCW, LOW);
  analogWrite(R_E, R_Speed);
}
void R_CCW(){
  digitalWrite(R_E, LOW);
  digitalWrite(R_MCW, LOW);
  digitalWrite(R_MCCW, HIGH);
  analogWrite(R_E, R_Speed);
}
void R_Brake(){
```

```
  digitalWrite(R_E, LOW);
  digitalWrite(R_MCW, LOW);
  digitalWrite(R_MCCW, LOW);
  analogWrite(R_E, HIGH);
}
void RS_Forward(){
  digitalWrite(RS_E, LOW);
  digitalWrite(RS_MF, HIGH);
  digitalWrite(RS_MB, LOW);
  analogWrite(RS_E, Rear_Speed);
}
void RS_Backward(){
  digitalWrite(RS_E, LOW);
  digitalWrite(RS_MF, LOW);
  digitalWrite(RS_MB, HIGH);
  analogWrite(RS_E, Rear_Speed);
}
void RS_Brake(){
  digitalWrite(RS_E, LOW);
  digitalWrite(RS_MF, LOW);
  digitalWrite(RS_MB, LOW);
  analogWrite(RS_E, HIGH);
}

void Roof_Right_Open(){
  digitalWrite(RR_E, LOW);
  digitalWrite(RR_MO, HIGH);
  digitalWrite(RR_MC, LOW);
  analogWrite(RR_E, Roof_Speed);
}
void Roof_Right_Close(){
  digitalWrite(RR_E, LOW);
  digitalWrite(RR_MO, LOW);
  digitalWrite(RR_MC, HIGH);
  analogWrite(RR_E, Roof_Speed*0.56);
}
void Roof_Right_Brake(){
  digitalWrite(RR_E, LOW);
  digitalWrite(RR_MO, LOW);
  digitalWrite(RR_MC, LOW);
  digitalWrite(RR_E, HIGH);
}
void Roof_Left_Open(){
  digitalWrite(RL_E, LOW);
  digitalWrite(RL_MO, HIGH);
  digitalWrite(RL_MC, LOW);
  analogWrite(RL_E, Roof_Speed);
```

```
}
void Roof_Left_Close(){
 digitalWrite(RL_E, LOW);
 digitalWrite(RL_MO, LOW);
 digitalWrite(RL_MC, HIGH);
 analogWrite(RL_E, Roof_Speed*0.56);
}
void Roof_Left_Brake(){
 digitalWrite(RL_E, LOW);
 digitalWrite(RL_MO, LOW);
 digitalWrite(RL_MC, LOW);
 digitalWrite(RL_E, HIGH);
}

// --------------------------VOID SETUP---------------------

void setup() {
Serial.begin(9600);
//Set Pinmodes
pinMode (Rear, INPUT); pinMode (Arm, INPUT); pinMode (Drive, INPUT);
pinMode (Social, INPUT); pinMode (Entry, INPUT);

pinMode (R_P, INPUT); pinMode (L_P, INPUT);

pinMode (L_E, OUTPUT); pinMode (L_MF, OUTPUT); pinMode (L_MB, OUTPUT);

pinMode (R_E, OUTPUT); pinMode (R_MCW, OUTPUT); pinMode (R_MCCW, OUTPUT);

pinMode (RS_E, OUTPUT); pinMode (RS_MF, OUTPUT); pinMode (RS_MB, OUTPUT);

pinMode (RR_E, OUTPUT); pinMode (RR_MO, OUTPUT); pinMode (RR_MC, OUTPUT);

pinMode (RL_E, OUTPUT); pinMode (RL_MO, OUTPUT); pinMode (RL_MC, OUTPUT);

pinMode (A_E, OUTPUT); pinMode (A_MU, OUTPUT); pinMode (A_MD, OUTPUT);
}

// --------------------------MAIN LOOP---------------------
void loop() {

//Rear Seat Toggle Position
 Rear_Button = digitalRead(Rear);
 if(Rear_Button == HIGH){
  RS_Forward();
 }
 if(Rear_Button == LOW){
  RS_Backward();
```

```
  }

//ArmRest Toggle Position

  Arm_Button = digitalRead(Arm);
  if (Arm_Button == HIGH && S_Arm == 1;) {
    C1_Arm = millis();
    Arm_Down();
    S_Arm = 0;
  }
    if (Arm_Button == HIGH && S_Arm == 0;) {
    C1_Arm = millis();
    Arm_Down();
    S_Arm = 1;
  }


//Command Roof

  Door_Open_Button = digitalRead(Door_Open);
  while (Door_Open_Button == HIGH) {
    Door_Open_Button = digitalRead(Door_Open);
    Roof_Right_Open();
    Roof_Left_Open();
    //delay(100);
    Serial.println("roof Opening");
  }
  if (Door_Open_Button == LOW) {
    Roof_Right_Brake();
    Roof_Left_Brake();
  }

  Door_Close_Button = digitalRead(Door_Close);
  while  (Door_Close_Button == HIGH) {
    Door_Close_Button = digitalRead(Door_Close);
    Roof_Right_Close();
    Roof_Left_Close();
    //delay(100);
    Serial.println("roof Closing");
  }
  if (Door_Close_Button == LOW) {
    Roof_Right_Brake();
    Roof_Left_Brake();
  }
```

```
//read potent. position
  PotRead_L = analogRead(L_P);
  PotRead_R = analogRead(R_P);

  //Measure the travel
  Travel_L = abs(PotRead_L - PotRead_L0);  //linear distance traveled.  L0 pot read is initial position
  L_Speed = constrain(map(Travel_L, 0, Travel_L_Max*0.25, L_Speed_Min, L_Speed_Max), L_Speed_Min, L_Speed_Max);  //constrain to keep speed from over 255
  Travel_R = abs(PotRead_R - PotRead_R0);
  R_Speed = constrain(map(Travel_R, 0, Travel_R_Max*0.4, L_Speed_Min, L_Speed_Max), L_Speed_Min, L_Speed_Max); //.4 is r ramp, do not change this to a variable


  if (Travel_L > (Travel_L_Max*0.6)) { //ramp down
    L_Speed = constrain(map(Travel_L, Travel_L_Max*0.6, Travel_L_Max, L_Speed_Max, (L_Speed_Min-70)), (L_Speed_Min-70), L_Speed_Max); //cant just adjust minspeed also adjust L_speed_min
  }
  if (Travel_R > (Travel_R_Max*0.6)) {
    R_Speed = constrain(map(Travel_R, Travel_R_Max*0.6, Travel_R_Max, R_Speed_Max, (R_Speed_Min-50)), (R_Speed_Min-50), R_Speed_Max);
  }


/*                                        DRIVE MODE                              */


  Drive_Button = digitalRead(Drive);
  if (Drive_Button == HIGH && S_Drive == 0) {
    S_Drive = 1;
    PotRead_L0 = PotRead_L;
    Travel_L_Max = abs(L_Driving - PotRead_L0);
    PotRead_R0 = PotRead_R;
    Travel_R_Max = abs(R_Driving - PotRead_R0);
    Serial.println();
    Serial.println("Drive Button--------------------------------------------------------");
  }
  if (S_Drive == 1) {
    if (PotRead_L > (L_Driving+20)) { //20 is tolerance for error
      L_Backward();
    }
    else if (PotRead_L < (L_Driving-20)) {
      L_Forward();
    }
    else {
      L_Brake();
      S_L = 1;
```

```
      Serial.println("Linear Done");
    }
    if (PotRead_R > (R_Driving+20)) {
      R_CW();
    }
    else if (PotRead_R < (R_Driving-50)) {
      R_CCW();
    }
    else {
      R_Brake();
      S_R = 1;
      Serial.println("Rotational Done");
    }
    if (S_L == 1 && S_R ==1){
      S_L = 0;
      S_R = 0;
      S_Drive = 0;
      Front123 = 1;   //Set Drive Mode
      Serial.println("Drive Mode Done------");
    }
  }

/*                              SOCIAL MODE                              */

  Social_Button = digitalRead(Social);
  if (Social_Button == HIGH && S_Social == 0) {
    S_Social = 1;
    PotRead_L0 = PotRead_L;
    Travel_L_Max = abs(L_Social - PotRead_L0);
    PotRead_R0 = PotRead_R;
    Travel_R_Max = abs(R_Social - PotRead_R0);
    Serial.println();
    Serial.println("Social Button----------");
  }
  if (S_Social ==1) {
    if (PotRead_L > (L_Social+20)) {
      L_Backward();
    }
    else if (PotRead_L < (L_Social-20)) {
      L_Forward();
    }
    else {
      L_Brake();
      S_L = 1;
      Serial.println("Linear Done");
    }
    if (PotRead_R > (R_Social+50)) {
```

```
      R_CW();
    }
    else if (PotRead_R < (R_Social-20)) {
      R_CCW();
    }
    else {
      R_Brake();
      S_R = 1;
      Serial.println("Rotational Done");
    }
    if (S_L == 1 && S_R ==1){
      S_L = 0;
      S_R = 0;
      S_Social = 0;
      Front123 = 3; // Set Social Mode
      Serial.println("Social Mode Done----------");
    }
  }

/*                                   ENTRY MODE                                   */

  Entry_Button = digitalRead(Entry);
  if (Entry_Button == HIGH && S_Entry == 0) {
    S_Entry = 1;
    PotRead_L0 = PotRead_L;
    Travel_L_Max = abs(L_Entry - PotRead_L0);
    PotRead_R0 = PotRead_R;
    Travel_R_Max = abs(R_Entry - PotRead_R0);
    Serial.println();
    Serial.println("Entry Button -----");
  }
      if (S_Entry == 1) {
        if (PotRead_L > (L_Entry+20)) {
          L_Backward();
        }
        else if (PotRead_L < (L_Entry-20)) {
          L_Forward();
        }
        else {
          L_Brake();
          S_L = 1;
          Serial.println("Linear Done");
        }
        if (PotRead_R > (R_Entry+30)) {
          R_CW();
        }
        else if (PotRead_R < (R_Entry-30)) {
```

```
          R_CCW();
        }
        else {
          R_Brake();
          S_R = 1;
          Serial.println("Rotational Done");
        }
        if (S_L == 1 && S_R ==1){
          S_L = 0;
                S_R = 0;
                S_Entry = 0;
                Front123 = 2; //Set Entry Mode
                Serial.println("Entry Mode Done ------");
             }
        }

  delay(30);
}
```

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