VEHICLE PERFORMANCE ANALYSIS OF AN AUTONOMOUS ELECTRIC SHUTTLE MODIFIED FOR WHEELCHAIR ACCESSIBILITY

Johan Fanas Rojas, M.S.E.

Western Michigan University, 2020

Autonomous vehicles (AV) have the potential to vastly improve independent, safe, and cost-effective mobility options for individuals with disabilities. However, accessibility considerations are often overlooked in the early stages of design, resulting in AVs that are inaccessible to people with disabilities. The needs of wheeled mobility device users can cause significant vehicle design changes due to requirements for stepless ingress/egress and increased space for onboard circulation and securement. Vehicles serving people with disabilities typically require costly aftermarket modifications for accessibility, which may have unforeseen impacts on vehicle performance and safety, particularly in the case of automated vehicles. In this research, we investigate the performance of three autonomous shuttle design configurations: an off the shelf shuttle that is not wheelchair accessible, the campus pilot shuttle that is wheelchair accessible, and a new design using wheelchair accessibility foresight. Physics-based simulations performed using MATLAB, ADAMS, and Autonomie demonstrated that the modifications aimed at providing wheelchair access had important implications for vehicle dynamics (e.g., turning radius, pitch, roll) and energy consumption (operating range and usage duration). A ride comfort analysis was performed using MATLAB to study the passenger's ride comfort in all three-shuttle designs. Also, energy consumption and lateral dynamic analyses were performed to analyze the operating range and turning radius of the shuttles. Since modern suspension systems are being integrated with an active control suspension system, an active control suspension model was developed in order to observe the benefits of incorporating this technology into our new design. In order to test the control system of the active suspension developed, a co-simulation was performed using ADAMS and MATLAB. Simulation results indicate that integrating this suspension system provides substantial benefits to ride comfort. The campus pilot shuttle design adversely affects the turning radius and reduces driving range by 38% while the new design makes no compromises in vehicle dynamics or driving range. We conclude that if wheelchair access and related accessibility considerations are incorporated in the design phase, the adverse performance of aftermarket modifications can be avoided.

VEHICLE PERFORMANCE ANALYSIS OF AN AUTONOMOUS ELECTRIC SHUTTLE MODIFIED FOR WHEELCHAIR ACCESSIBILITY

by

Johan Fanas Rojas

A thesis submitted to the Graduate College in partial fulfillment

of the requirement for the degree of Master of Science in Engineering

Mechanical Engineering

Western Michigan University

March 2020

Thesis Committee:

Zachary Asher, Ph. D., Chair

Mitchel Keil, Ph. D.,

Kapseong Ro, Ph.D.,

ACKNOWLEDGMENTS

I would like to thank Dr. Zachary Asher for his support in my research and during this project. His constant encouragement and productive feedback allowed me to be successful during my Master's degree at Western Michigan University. Also, I would like to thank both of my committee members, Dr. Mitchel Keil and Dr. Kapseon Ro, for providing their modeling and simulation expertise and making significant contributions to my research.

This project was carried out thanks to the support of the Michigan Department of Transportation (MDOT). I would also like to thank Pratt & Miller Engineering for leading the project and their contributions to vehicle redesign. I extend my gratitude to Matt Lesh at Comet Mobility and Anthony Navarro at Polysinc for their support on this project. Also, I would like to thank all other team members, including Robotic Research, Kevadiya, and Easterseals.

Johan Fanas Rojas

Table of Content

List of Figures

List of Tables

List of Symbols

z_b	Vehicle body vertical displacement (Sprung mass displacement)
θ	Pitch angle
Φ	Roll angle
I_{yy}	Pitch axis moment of inertia
I_{xx}	Roll angle moment of inertia
l_f	Front tire – GC distance
l_r	Rear tire – CG distance
m_b	Vehicle mass (Sprung mass)
b_r	Right tire – CG distance
b_l	Left tire – CG distance
K_{fr}	Front right spring stiffness coefficient
K_{rr}	Rear right spring stiffness coefficient
K_{fl}	Front left spring stiffness coefficient
K_{rl}	Rear left spring stiffness coefficient
C_{fr}	Front right damping coefficient
C_{rr}	Rear right damping coefficient
C_{fl}	Front left damping coefficient
C_{rl}	Rear left damping coefficient
z_{ufr}	Unsprung mass displacement (front right tire displacement)
z_{urr}	Unsprung mass displacement (rear right tire displacement)
z_{ufl}	Unsprung mass displacement (front left tire displacement)

z_{url} Unsprung mass displacement (rear left tire displacement)

z_{rfr} Displacement input (front right)

z_{rrr} Displacement input (rear right)

z_{rfl} Displacement input (front left)

z_{rrl} Displacement input (rear left)

F_{fr} Force acting upon the sprung mass due to the spring and damper (front right)

F_{rr} Force acting upon the sprung mass due to the spring and damper (rear right)

F_{fl} Force acting upon the sprung mass due to the spring and damper (front left)

F_{rl} Force acting upon the sprung mass due to the spring and damper (rear left)

F_{afr} Control force on front right tire

F_{arr} Control force on rear right tire

F_{afl} Control force on front left tire

F_{arl} Control force on right left tire

F_{wfr} Force acting upon the unsprung mass due to tire stiffness (front right)

F_{wrr} Force acting upon the unsprung mass due to tire stiffness (rear right)

F_{wfl} Force acting upon the unsprung mass due to tire stiffness (front left)

F_{wrl} Force acting upon the unsprung mass due to tire stiffness (rear left)

1. Introduction and Literature Review

1.1 Accessibility

Accessibility means a product, device or service that is usable to all. Accessibility concerns giving equal opportunities to everyone, no matter their ability or the circumstances. When designing a system, accessibility should be considered in the development process. This way, you are ensuring that your system is accessible to all potential users. Even though we have regulations to avoid limitations for some individuals, people with disabilities still face challenges when it comes to accessible products. People with disabilities are just as diverse as people without disabilities. There are many types of disabilities. These vary from visual impairment, hearing impairment, mobility impairment, etc.

1.1.1 Transportation and individuals with disabilities

Transportation plays a vital role in an individual's ability to participate in society. The ability to travel outside the home allows opportunities for employment, recreation, and fulfillment of needs. In order for individuals to obtain employment, goods and services, healthcare, education, and interact socially, access to transportation is critical. In transportation, this is reflected in the ability of the transport system to provide to all members of a society the same level of access to different opportunities. When access/social rights are not secured, and a population is at a disadvantage, social exclusion occurs. Individuals who face difficulties in gaining this access are considered 'transportation disadvantaged.' Those disadvantaged include individuals of lower socioeconomic status, aging individuals, and persons with disabilities. In our auto-dependent society, individuals with disabilities face even less opportunity to interact with their communities. Approximately six million individuals with disabilities have mobility difficulties. The lack of transportation for these individuals, causes a loss of $19 billion annually in missed medical appointments. More than 4.3 million people use wheeled mobility devices. This number is expected to grow by 7% annually due to aging and increases in mobility impairments.

1.1.2 Transportation challenges for individuals with disabilities

Individuals with disabilities face barriers when it comes to public/private transportation due to the lack of appropriate vehicle and facility design. Some challenges of bus transportation include inoperable lifts and ramps, false claims of inoperable lifts or ramps to avoid boarding a person with a disability, failure to stop for a traveler with a disability, attitudinal barriers among drivers, the steep slope for ramp use, failure to clear wheelchair securement zones for people with disabilities, failure to provide stop announcements, and failure to provide route identification. Some studies have shown that two-thirds of all people with disabilities have an income below $35,000, and that their transportation problems are related to their low income [9]. Restriction to transportation affects these individual's quality of life, social participation with the community, job employment, etc. [10] Many people with disabilities never leave their homes because of the lack of transportation and inadequate accessible systems.

1.1.3 Vehicle designs and wheelchair users

Accessible transportation is essential for achieving community integration and reducing social disparities among people with disabilities. Despite the passage of federal regulations concerning accessible public transportation [11][12][13], individuals with disabilities still face accessibility and usability barriers stemming from the inadequate design of public transportation vehicles. Users of wheeled mobility devices are particularly impacted by poor vehicle design due to their need for stepless ingress/egress to vehicles (e.g., by using either access ramps, lifts, or level-boarding), sufficient clear floor space for on-board maneuvering and positioning the device during travel, and occupant securement. Vehicle designers face challenges in designing to accommodate the wide range of wheeled mobility devices, oversized devices, larger and heavier devices such as scooters, tie-down attachments, and independent securement systems[14]. Accessibility is usually an afterthought in the vehicle design process, and retrofitting vehicles with accessibility features is more costly than considering them in the early design process.

1.1.4 Post-production modifications to vehicles

One-third of all the individuals with disabilities report they are not active drivers due to the limitations they possess or the cost of retrofitting a vehicle for accessibility. The cost of retrofitting a vehicle with special features for these individuals to drive or act as a passenger (in case of a wheelchair user) is very high, and it's between $20,000-$80,000 on top of the purchase price of the vehicle[15]. Therefore, many individuals decide to use public transportation instead, but public transportation also lacks some features for it to be accessible to all individuals. A vehicle with post-production modifications for wheelchair accessibility is shown in Figure 1. Even though the automotive industry has been active during decades, accessibility hasn't been considered in the early design process.

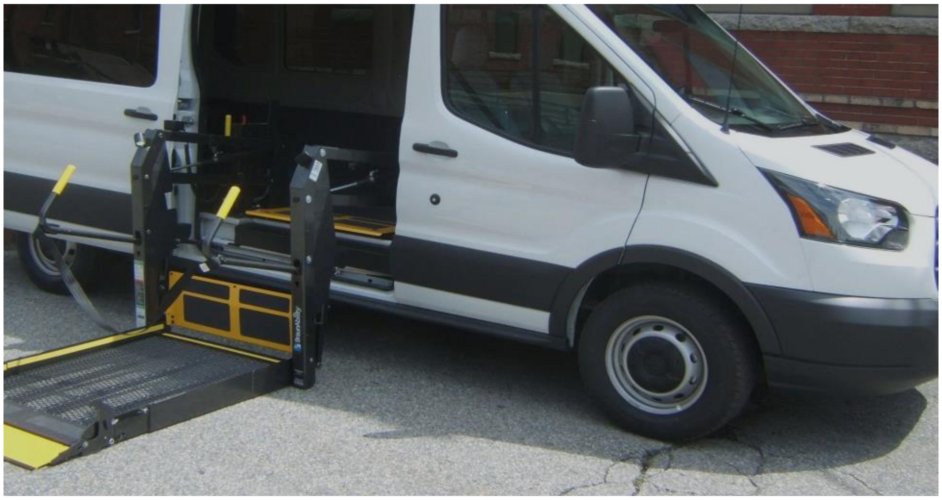


Figure 1. Post-production modification to a vehicle

Autonomous vehicles can provide independence for these individuals if they are designed to be accessible from the early design process. Individuals with disabilities prefer the concept of an AV, because it releases them from the interaction between the vehicle and the human. The modifications required for a wheelchair user are more expensive because they need features for the ingress, inboard space, and restraints. The challenge lies in making these modifications without compromising the vehicle's performance and, at the same time, maintaining a low cost [16].

1.2 Autonomous vehicles

An autonomous vehicle is a vehicle that is capable of sensing its environment and driving safely with no human input. Self-driving vehicles must go through several stages in order to drive autonomously. These stages are perception, path planning, and vehicle control. In the perception stage, the vehicle perceives the environment with the help of sensors. These sensors can be a camera, GPS, lidars, and radars. After perceiving what is around it, the vehicle should plan its trajectory safely from its current destination to its final destination. Vehicle control is achieved by control the longitudinal and lateral maneuvers of the vehicle. The planning and vehicle control is performed by algorithms that determine the safest path (in the planning stage) or the necessary vehicle input (in the vehicle control) to achieve the desired objective.

There are certain levels of autonomy when it comes to self-driving vehicles. Figure 2 shows the levels of automation defined by SAE. At level 0, the driver performs all driving tasks. Level 1 indicates that the vehicle is capable of controlling either the lateral or longitudinal motion of the vehicle. Nowadays, almost all vehicles come with this type of technology. In level 2, the vehicle is capable of controlling both the lateral and longitudinal motion of the vehicle and detection events. For example, the proximity of other cars when going in reverse. In level 3, the vehicle is able to perceive the environment, and it’s capable of most driving tasks, but the human override is still required. In level 4, the vehicle performs all driving tasks, but the human must intervene if requested. Level 5 is the full automation of the vehicle. The passenger doesn’t intervene in any driving operation of the vehicle.

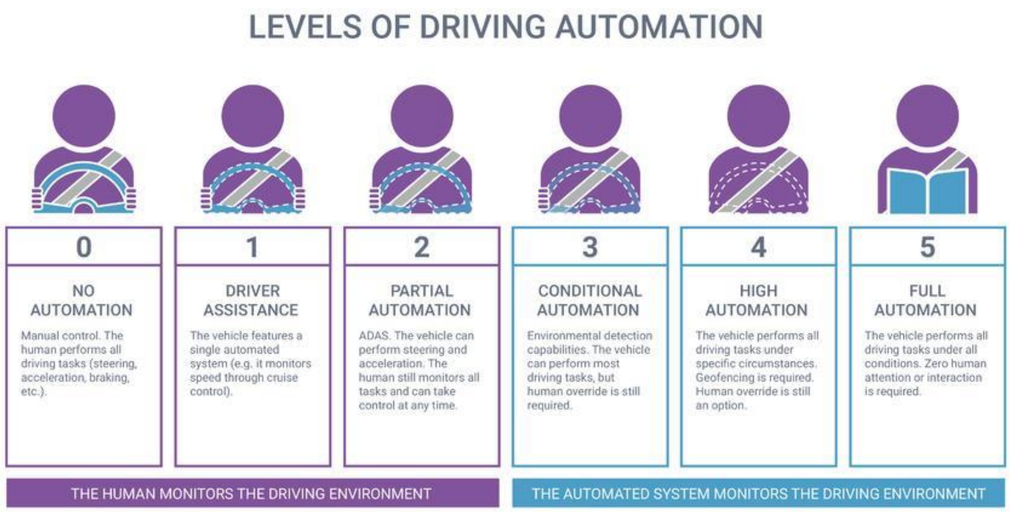


Figure 2. Levels of autonomy for self-driving vehicles

1.3 Vehicle dynamics

Vehicle dynamics is concerned with the movement of vehicles on a road surface. These movements are acceleration, braking, ride, and handling [17]. Vehicle dynamics study the forces acting on the vehicle when the tires are submitted to a given input; for example: steering input, vertical displacement, angular velocity, etc. The dynamics of a vehicle have a major impact on a vehicle’s performance, and it varies withing each vehicle design.

The essential systems of vehicle dynamics are the vehicle body (sprung mass), tires (unsprung mass), and the suspension components (spring and damper). Vehicle dynamics is divided into longitudinal, vertical, and lateral dynamics. Longitudinal dynamics study the forces acting upon the vehicle when accelerating and braking, lateral dynamics concerns handling scenarios of the vehicle and vertical dynamics involves ride comfort and vibration caused by vertical tire forces [18].

1.4 Autonomous vehicles and accessibility

Figure 3. Accessible autonomous vehicle

Autonomous vehicles (AVs) have the potential to increase independent and safe mobility options for many transportation-disadvantaged groups, including older adults and people with disabilities [19][20][21]. However, AVs also introduce new challenges for accessible design due to the absence of drivers or attendants who would typically provide assistance to passengers with disabilities during tasks such as ingress/egress, onboard circulation, and wheelchair securement. Figure 3 illustrates the ideal case of an accessible autonomous shuttle that doesn't require assistance for passengers with disabilities. The design of AVs may require a higher standard of accessibility to ensure that passengers with disabilities can independently use these vehicles without driver assistance.

Recent studies on the anthropometry of wheeled mobility devices provide evidence for the increased size and diversity of these devices. It is necessary to increase the minimum clear floor space dimensions specified in accessibility standards for accommodating wheelchairs on transport vehicles [22][23][24]. Comparisons with wheelchair anthropometry data from other countries such as, the UK and Canada, suggest similar trends [25]. Collectively, these findings reflect the need for AV designers and manufacturers to understand and account for changes in contemporary assistive technology and user needs when designing vehicles intended for users of wheeled mobility devices.

1.5 Vehicle dynamics and automotive accessibility

Accessible vehicles increase mobility for individuals with disabilities, but they tend to increase fatigue and discomfort in passengers due to poor vehicle design. Previous studies have indicated that the vehicle's floor vibration is responsible for this discomfort [26]. A vehicle design varies depending on the type of disability the user possesses. In the case of a wheelchair user (which vehicle designs require more additional features), several variables need to be considered like weight, space, ingress/egress, and type of securements. The weight of a wheelchair can vary significantly; therefore, suspension tuning must be done to accommodate this wide working range [27]. Simulation software is used to model the ride comfort when handling, and road disturbances are present. Hence, vehicle dynamics play an important role when it comes to accessible vehicle design. Vehicle vibrations affect the passenger's health and comfort. Throughout the years, many studies have been carried out in order to decrease these vibrations, including suspension tuning, control strategies, etc. [28]

1.6 Vehicle dynamics and autonomous vehicles

Research on autonomous vehicles has mainly focused on perception, planning, and control. Autonomous vehicles that possess a low level of control usually use a predefined trajectory (route). Nevertheless, due to the presence of obstacles, pedestrians, and other traffic scenarios, the autonomous vehicle relies on Model Predictive Control (MPC) for motion control. MPC contains a model of vehicle dynamics to find feasible control inputs [29]. Control of the vehicle dynamics of an autonomous vehicle in the decision-making process is crucial because of uncertainties and safety risks [30]. Obstacle avoidance and planning trajectory in a dynamic environment is a challenging and vague task if we don't consider the kinematics of the vehicle during driving scenarios. An autonomous vehicle must be capable of reacting like a human driver when encounters uncertain road disturbances. For example, if the wheels are slipping, it should be able to adjust its control system to avoid the collision. Vehicle stability control systems are used to stabilize the vehicle in extreme handling conditions [31]. It is important to note that control systems for an AV's kinematics have been in research for a few years. Cornell University's Team for the

2005 DARPA Challenge used a path planner algorithm using a feedback loop to generate smooth paths that are consistent with vehicle dynamics [32].

Ergonomics is also something that has been studied in vehicles for decades, and that is considered in autonomous vehicles. Ergonomics include ride comfort, vehicle motion, noise, etc. Passengers are exposed to road and load disturbances due to braking, acceleration, and handling [33]. The vertical vibration exerted to passengers is a parameter that engineers have approached for several years by implementing semi-active and active suspension systems. An autonomous vehicle's controllability and ride comfort are concepts considered when path planning [34]. An AV's dynamics influence its path motions, and lateral control strategies are used to minimize the errors between the desired and actual path [35].

1.7 Novel contribution

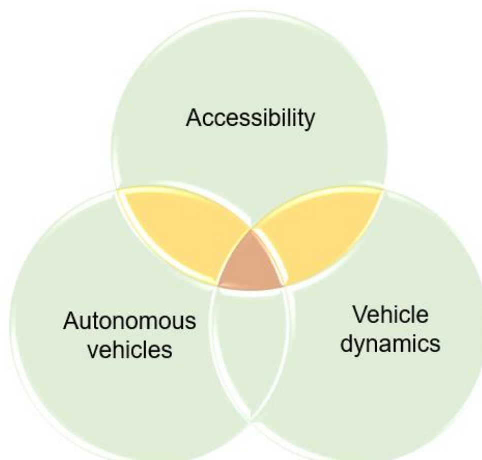


Figure 4. Relationship between these three research topics and the existing gap

The three topics involving this research are accessibility, autonomous vehicles, and vehicle dynamics. The Venn Diagram shown in Figure 4, represents these three research topics, their overlap, and their research gap. These topics haven't been combined to analyze the vehicle dynamics of an autonomous vehicle when retrofitted for accessibility. Accessibility is a well-known topic, and it has been studied for many years [36]. Accessibility can be a general term and can be defined in various ways, but for this study, our interest is accessibility for individuals with disabilities [37][38]. Accessibility involves accommodating a product or environment to be "Universally accessible." This topic has been deeply studied by the Americans With Disabilities Act (ADA), and they have regulations concerning how to address accessibility issues for all people

[39]. Autonomous vehicles and accessibility are topics that are considered very poor because nowadays, vehicles are modified post-production to accommodate individuals with disabilities.

Vehicle dynamics is a research area that has been studied for decades, and it's considered in vehicle designs [40][41]. From the previous section, we saw that vehicle dynamics and the autonomous vehicle is also a known research area. Vehicles currently possess technologies with a certain level of autonomy, and they are used to aid the driver in certain situations [42][43]. Even though accessibility and vehicle dynamics are two well-known topics, there is a big gap between them due to afterthoughts considerations for accessibility in vehicle designs. These considerations impact the vehicle's dynamic, and it's not considered in the early design process. There is a few ongoing research considering accessibility and vehicle dynamics on vehicle designs.

These three topics combined is a research area that hasn't been considered. The purpose of our research is to study those three fields and provide some benefits and implications of considering them in the design of autonomous vehicles.

2 Scope of the project at Western Michigan University

The overall goal of this demonstration project was to expand transportation options for disabled students at Western Michigan University (WMU), by modifying two commercially available automated electric shuttles for wheelchair-accessibility. WMU's campus had transportation to transport disabled students from their dormitories to class, but that program got canceled. In order to provide hours of service for disabled students and integrate new transportation technologies, this project proposed the use of 4-passenger low-speed (up to 15 mph) electric automated (SAE Level-4) shuttles (Aurrigo PodZero, RDM Group, UK) operating on a fixed route on Western Michigan University's campus. The Aurrigo PodZero design is shown in Figure 5. The project was supported through the Michigan Mobility Challenge, a program designed by the Michigan Department of Transportation to fund pilot transportation projects that solve mobility challenges for seniors, persons with disabilities, and veterans throughout Michigan.

Figure 5. Aurrigo PodZero design

A key limitation of the shuttle as built was its inability to accommodate a wheeled mobility device primarily due to inadequate clear floor space and a 255 mm step height for ingress/egress. To accomplish the objective of achieving wheelchair access, substantial modifications to the vehicle chassis and passenger compartment were undertaken to address four key design objectives:

1. Increase the available clear floor space by translating the front and rear axles, thereby elongating the wheelbase.
2. Installing a retractable access ramp beneath the vehicle floor to allow for stepless ingress/egress. Due to weight and power constraints, a manual ramp was selected over an automated ramp for this iteration.
3. Installing flip-up seats (vs. fixed seats) to increase the interior circulation space during ingress/egress and for situating a wheelchair during travel, while also ensuring seat availability for the vehicle operator and one additional passenger/companion. Due to constraints on the available floor space and comparisons with wheelchair anthropometry data on occupied length, width [14], and weight capacity, the existing design was limited to accommodating only manual wheelchairs.
4. Provisions for a forward-facing, four-point wheelchair securement system and a lap/shoulder-belt occupant restraint system.

2.1 Operation of autonomous shuttles at Western Michigan University

The shuttles operated on a fixed route on Western Michigan University's main campus, picking up and dropping off students on seven pickup/drop-off points along the route. The shuttles worked on demand. A ride-hailing system was developed for the project so that students can select their current pickup point and their destination. A safety operator is always on board for safety purposes and to assist wheelchair users to ingress the shuttle. The pickup/drop-off points were selected based on the most visited buildings on the main campus by students with disabilities. The route of the shuttles is shown in Figure 6.

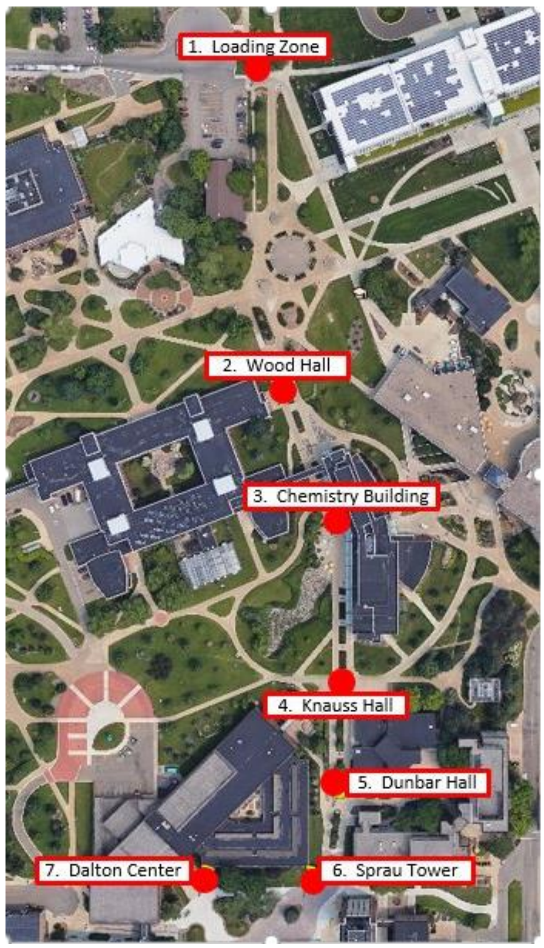


Figure 6. Route of the autonomous shuttle on Western Michigan University's main campus

2.2 Modifications of the autonomous shuttles for Michigan Mobility Challenge

In order to accommodate wheelchair users, the off-the-shelf design of Aurrigo had to be modified. In order to provide adequate turning space for a manual wheelchair during ingress/egress and positioning the wheelchair in a forward-facing position during travel, the wheelbase was increased from 1620 mm to 2280 mm. The increased wheelbase and installing of a retractable access ramp in the vehicle floor necessitated increased structural support to the chassis, which led to increased vehicle weight. Dimensions such as the vehicle height from the ground and the door width remained the same. Grab bars within the shuttle in both versions of the design are available on either side of the curb-side door.

Seating capacity remained the same at 4 seated passengers when no wheelchair was on board. The fixed seats were replaced with flip-up seats. When a wheelchair was on-board, a rear-facing flip-up seat was also available for a companion along with a side-facing flip-up seat located at the anterior of the compartment for the vehicle operator. Care was taken to ensure a minimum clear floor space of 1220 mm x 760 mm was available for accommodating an occupied wheelchair even with a vehicle operator and companion seated on board.

The off-the-shelf design had a battery pack of 6 x 8V lead-acid batteries. Since space from the battery pack was taken to increase the interior clear floor space, these were replaced with 4 x 12V lithium iron phosphate batteries causing a decrease in energy capacity from 8kWh to 4.8kWh. The campus pilot is shown in Figure 7.

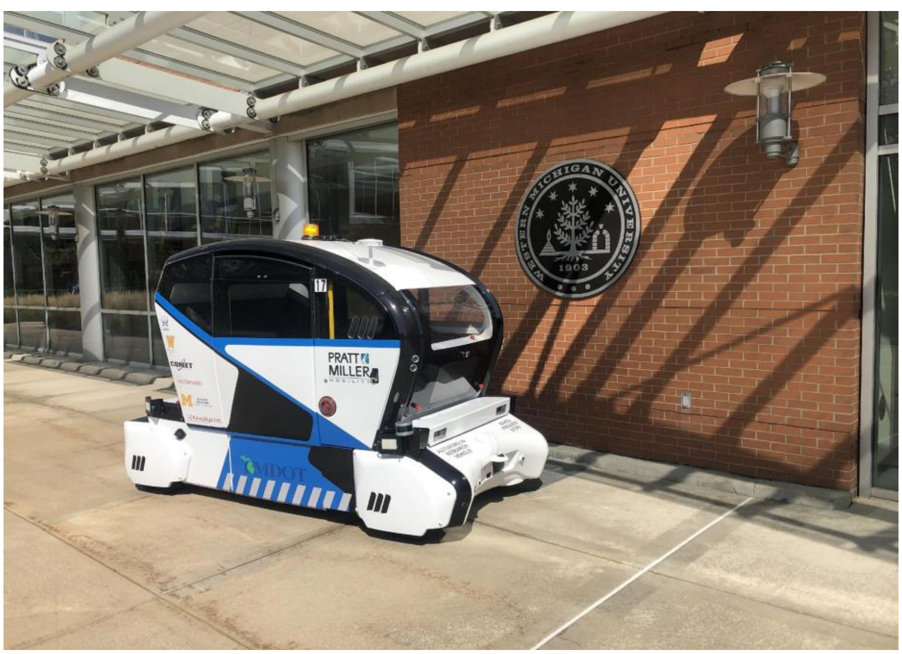


Figure 7. Campus pilot design accessible for wheelchair users

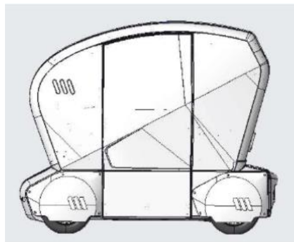
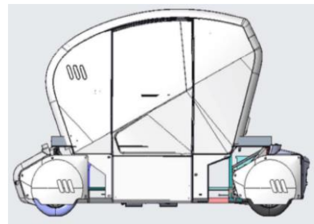
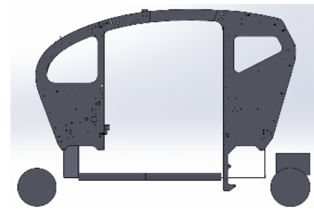
2.3 Scope of the current study and the project

In this project, an off-the-shelf autonomous shuttle from the UK was bought to provide hours of service to disabled students at Western Michigan University's main campus. The objective of this project was to expand transportation students, especially for wheelchair users and veterans; however, the off-the-shelf shuttle was not accessible for wheelchair accessibility and had to be modified. Several companies were part of this project and each with a given task. My colleague and I worked with the cost analysis, simulation, and other tasks that involved making the project successful. The other companies like Pratt & Miller Engineering worked with the modifications of the chassis, and Robotic Research integrated the sensors and the autonomy system, University of Michigan performed an accessibility study performed, etc.

Given the aforementioned limitations, post-production modifications were made to obtain an accessible shuttle. This fact brings us to our main points. What implications do we get with these post-production modifications? Do simulation tools give us insight into these implications? As we saw earlier, post-production modifications compromise the vehicle's performance. Hence, our intention is to analyze the performance before and after modifications for wheelchair accessibility. Also, incorporate a new design with all the requirements taken into account in the early design stage and compare it with previous designs. This design was introduced to analyze the advantages of considering accessibility in the early design process rather than being an afterthought. As mentioned in section 2.4 (Novel contribution), the combination of autonomous vehicles, accessibility, and vehicle dynamics has not been studied; therefore, this research will provide some insight on the advantages of designing an accessible autonomous shuttle by performing a vehicle performance analysis. Using MATLAB and ADAMS, provide implications on the ride quality and maneuverability of the shuttle after post-production modifications and that this can be avoided by considering accessibility in the early design process. Also, a cost analysis was performed to demonstrate that post-production is more costly than considering accessibility at the early design stage.

2.4 Engineering inputs

As we already know, post-production modifications are costly and compromise the vehicle's performance in some sort of way. Having that in mind, Table 1 illustrates the key specifications of all three designs for our analysis.

Design specifications	Off-The-Shelf Design	Campus Pilot Design	New Design
Shuttle design (side view)			
General Vehicle Specifications			
Wheelbase (mm)	1620	2280	2500
Seating capacity	4 passengers	4 passengers or 2 seated passengers and 1 passenger in	4 passengers or 2 seated passengers and 1 passenger in a wheelchair
Gross vehicle weight (lb)	2204	2350	2458
Battery type and configuration	6x8V lead acid batteries in series	4x12V lithium iron phosphate in series	6x12V Lithium iron phosphate batteries in series
Energy capacity (kWh)	8	4.8	8.4
Accessibility Specifications			
Door width (mm)	790	790 (unchanged)	819
Door height from vehicle floor (mm; at lowest point)	1450	1450	1450

Floor height from ground (mm)	255	255 (unchanged)	255
Ramp weight capacity (lbs)	N/A	450	600
Access ramp availability	No	Yes	Yes
Type of seats available	2-person forward facing bench seat + 2-person rear facing bench seat	2-person forward facing flip-up seat + 1-person rear facing flip-up seat + 1-person side facing flip-up seat	2-person forward facing flip-up bench seat + 2-person rear facing bench seat
Wheelchair securement	N/A	Forward facing 4-point active tie down	Forward-facing 4-point active tie-down
Interior clear floor space during ingress/egress (mm; all seats flipped up)	N/A	1275 length x 950 width	1950 length x 950 width (95%)
Clear floor space during travel (mm; bench flipped up) (% wheelchairs accommodated)	N/A	1135 length x 762 width (36%)	1385 length x 950 width (95%)
Accessible emergency stop button/brake availability	No	Yes	Yes

Acquisition cost ($)	85,000	105,000	90,000-95,000

Table 1. Comparison of specifications before and after redesign

We estimate that the off-the-shelf design of the autonomous shuttle costs around $85,000 since the sensor and software integration of an autonomous vehicle is approximately $50,000[44]. As we mentioned earlier, postproduction modifications for accessibility have serious impacts in terms of costs; therefore, we assumed an additional cost of $20,000 to make the shuttle accessible. For the new design, we assume an automotive manufacturing company designed the shuttle to be accessible; therefore, we will have a cost reduction in the manufacturing process. We estimate that the new design could be between $5,000-$10,000. This range is due to the few costs in additional materials needed to manufacture this design. Nevertheless, this cost range would depend on the type of modifications they add to the vehicle, for example, if they install ramps or lifts.

2.5 Survey to Non-riders

A survey of the students that didn't ride the autonomous shuttle was gathered in order to observe their perception of this technology and the impact these shuttles impose by operating on the sidewalk. This online survey was sent to the whole student body that is in their third year or under and took classes in the buildings close to the autonomous shuttle's route. A total of 308 students took the online survey, and this data was collected for research purposes. The results of our survey are shown in Figures 8 -13 Survey results indicate that the students have a positive perception towards autonomous vehicles and the level of risk they impose when operating in pedestrian walkways.

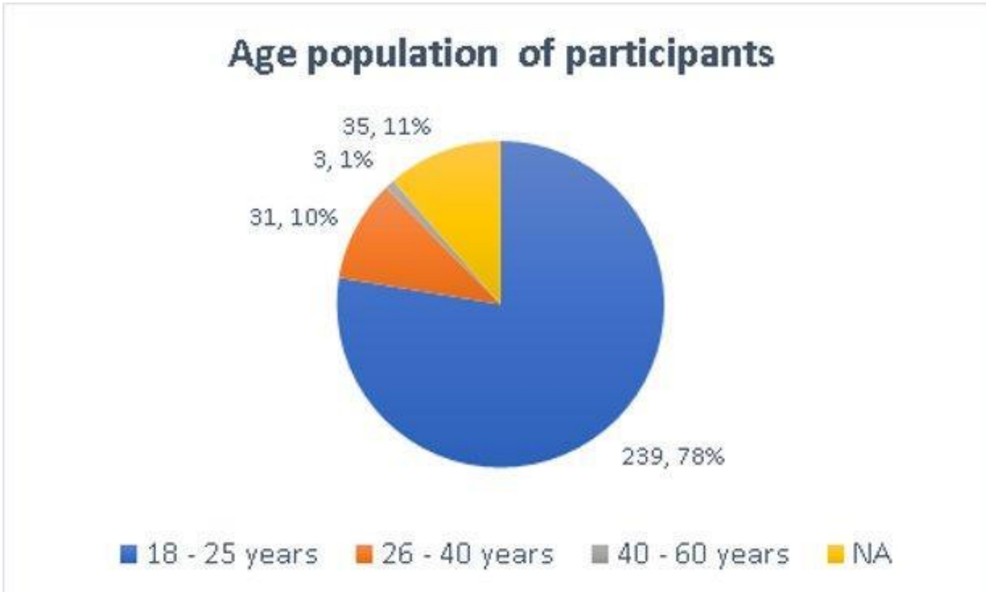


Figure 8. Age population of the participants that took the online survey

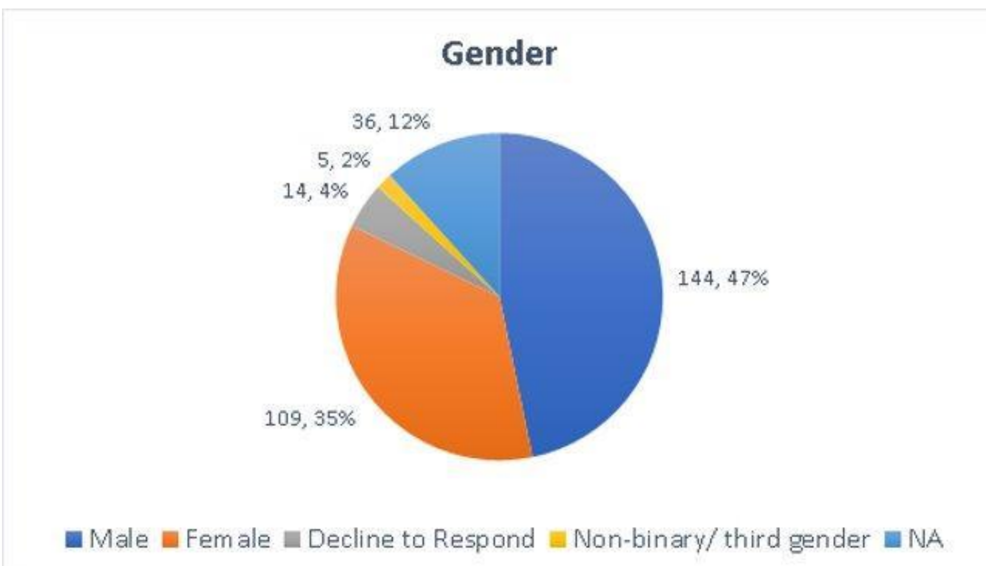


Figure 9. Gender of the participants who took the online survey

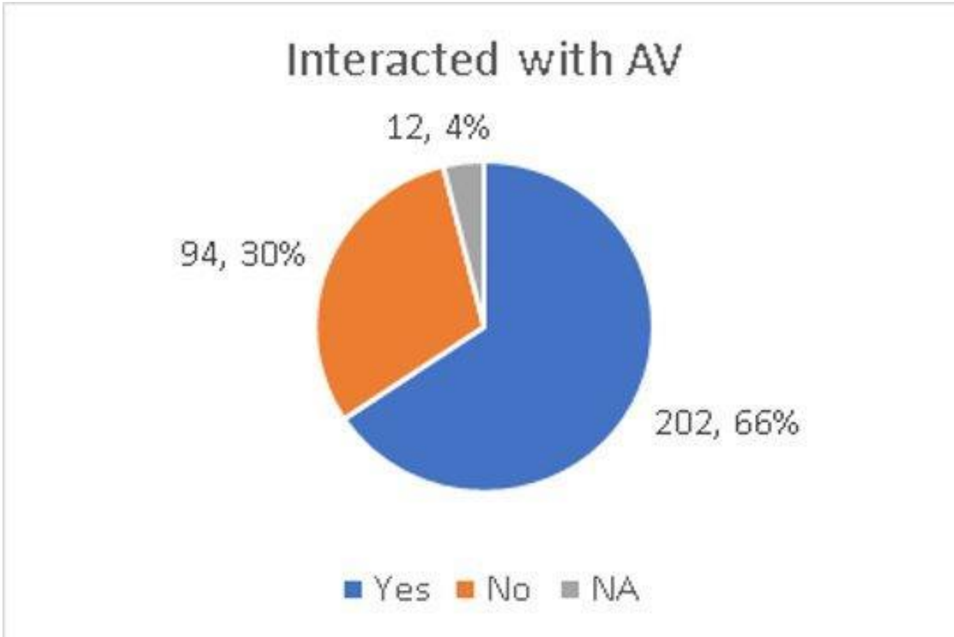


Figure 10. Population of the participants that interacted with the autonomous shuttle

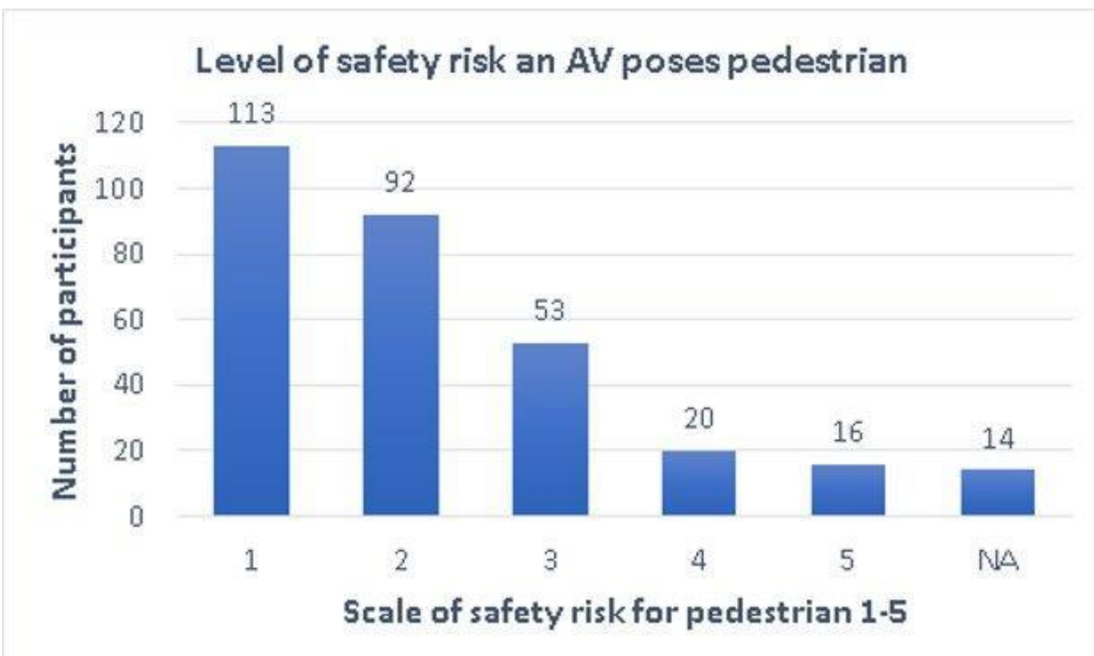


Figure 11. Perception of the level of risk imposed by the shuttle to the survey participants

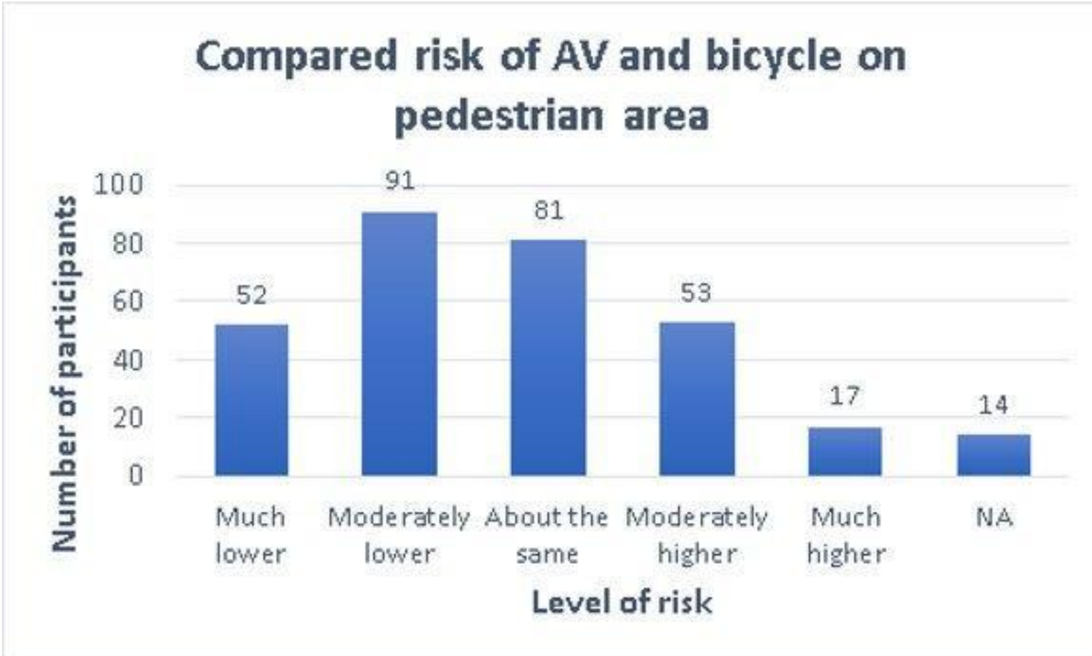


Figure 12. Risk comparison of an autonomous shuttle and a bicycle in the sidewalk

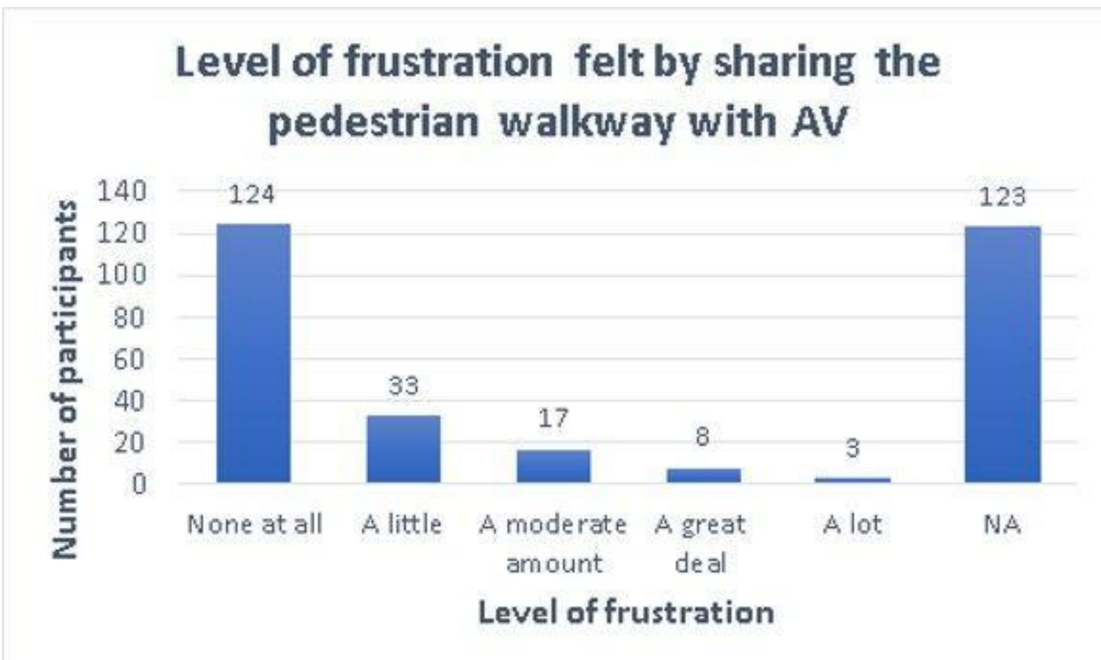


Figure 13. Level of frustration by survey participants when interacting with autonomous shuttle

3 Methodology

3.1 Vehicle Suspension system

A suspension system is a group of mechanical components used to connect the vehicle body and tires [45]. It allows motion between the body and the tires. The main function of the suspension system is to minimize the vehicle's vertical vibration and maintain road holding. Springs and dampers are considered suspension components, and they are used to reduce shock loads. There are several types of suspension systems, but the one used for this research study are independent suspensions. Also, suspension can be divided into two categories: passive and active suspensions.

3.1.1 Passive suspension model

Passive suspensions consist of traditional components like springs and dampers, which are time-invariant. These elements can only store (springs) or dissipate energy (dampers) [46]. These elements don't supply external energy to the suspension system. This type of suspension system has limitations when it comes to controlling a vehicle's dynamics. These limitations come from the fact that vehicles are operated on different road conditions and at different speeds while exerted to load changes and maneuvering. A representation of a passive suspension system is shown in Figure 14.

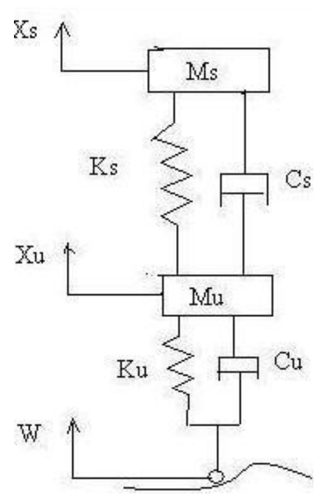


Figure 14. Representation of passive suspension system on quarter car model

3.1.2 Active suspension model

An active suspension system includes actuators that generate forces to the suspension system to minimize vibration on the vehicle body and improve ride quality. This type of suspension system possesses a control system that measures the relative displacement between the vehicle body and the tires and exerts a force to reduce vertical displacement between these two components. Figure 15 shows all the components of an active suspension system and the control diagram.

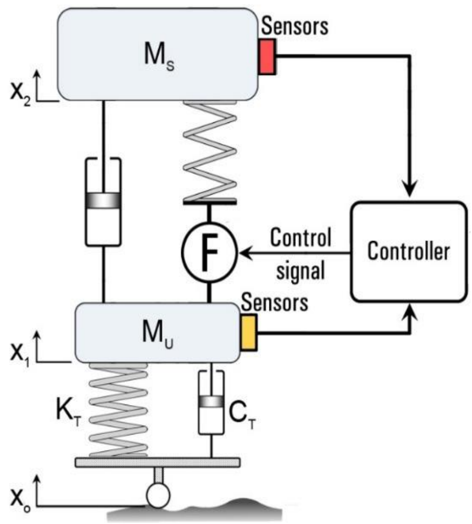


Figure 15. Representation of active suspension system on quarter car model

3.1.3 Skyhook Theory

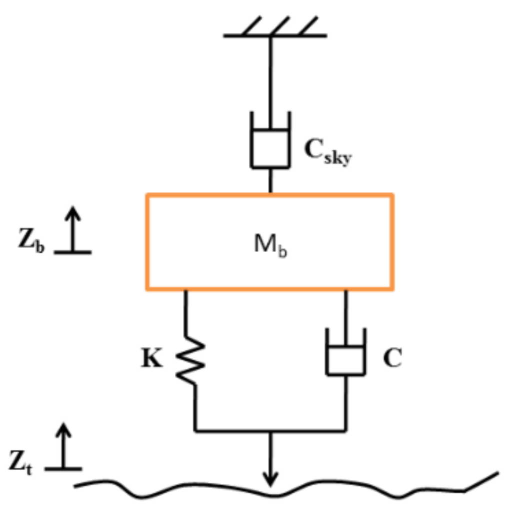


Figure 16. Representation of skyhook damping model

The skyhook damping theory consists of a fictitious damper attached to the sprung mass and the stationary sky (shown in Figure 16). This is a fictional configuration because of this to happen; the damper must be attached to a reference in the sky fixed in the vertical position. There exist several methods for optimal control techniques, but studies have indicated that skyhook control is the optimal control technique when it comes to isolating the sprung mass from road excitations. One method of implementing this in vehicles is by generating an active control force using hydraulic actuators, electronic actuation, etc. The skyhook damping method minimizes the vibration of the sprung mass by adding a variable damping force that depends on the relative velocity of the sprung and unsprung mass. For simplicity, we integrated the skyhook control theory to our analysis by generating a damping force to minimize the chassis' vertical acceleration. This damping force was generated by measuring the relative velocity between the sprung mass and the wheels and multiplying it by an assumed damping coefficient of 1 Ns/mm.

3.2 Pitch motion

Pitch refers to the angular displacement about the lateral axis during braking and acceleration of the vehicle as it moves forward or backward. The pitch of a vehicle determines the smoothness of the ride and vehicle responses to road excitations or road irregularities. Pitch angle is an important parameter for evaluating ride quality and its associations to passenger comfort [47].

3.3 Roll motion

The roll of a vehicle is the angular displacement about the longitudinal axis when cornering [48]. The weight shifts left or right due to the centrifugal force while handling. The roll of a vehicle also depends on the suspension fitted to the vehicle. The roll angle is an important parameter because it determines whether a vehicle is likely to rollover while traversing curves [49]. Suspension analysis was not considered in the present study.

3.4 Ride comfort study

The purpose of this research is to illustrate the consequences of considering accessibility as an afterthought in a design of an autonomous shuttle and to compare the performance of a custom shuttle design with the two shuttles used for the WMU project. A ride comfort analysis (assuming a passive suspension system) was performed using MATLAB. Also, an active suspension system was developed in MATLAB and compared with our passive suspension system model. The parameters considered for our ride comfort analysis were chassis vertical displacement and acceleration, roll angle, and pitch angle. This analysis was performed during different road conditions. A mathematical model of a full vehicle was derived and used for our analysis. Furthermore, a vehicle model was developed in ADAMS based on pictures of the autonomous shuttle. Since the developed ADAMS model contains the kinematics of the real shuttle, a co-simulation was performed between MATLAB and ADAMS in order to validate the active suspension system with our model.

3.4.1 Mathematical model

A mathematical model of a vehicle's vertical dynamics was derived from analyzing the vehicle's response to various road inputs. Our system possesses 7 degrees of freedom, and it is commonly used to study a vehicle's ride dynamics. The level of vibration exerted to passengers is an important criterion to evaluate ride comfort in a vehicle's designs, and its suspension system plays an important role. In our model, the chassis is viewed as a sprung mass and the tires as unsprung masses. Our interest is to analyze the behavior of the sprung mass due to different road conditions. Figure 17 represents our full vehicle model and the sign convention used to derive the equations of motion.

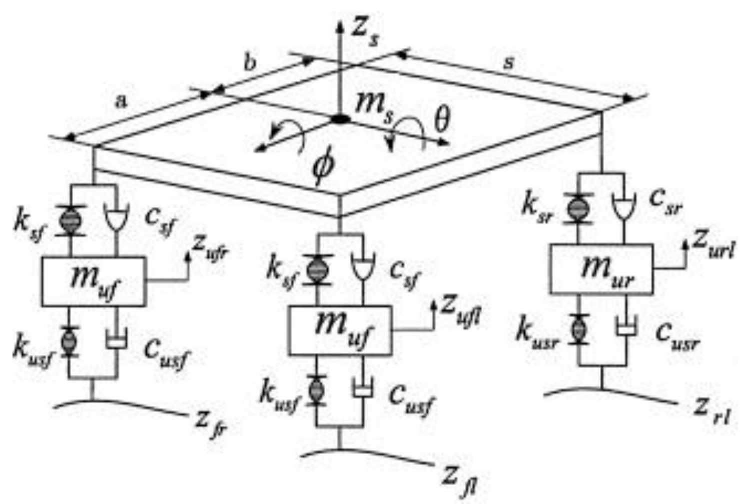


Figure 17. Mechanical model of vehicle suspension system

Since we have a 7 degree of freedom model, we need 7 equations of motion to describe the vertical motions of the vehicle body, the four tires, and the two rotations of the vehicle body. Hence, using Newton's laws of motion, we derived the following equations of our system.

$$\ddot{z}_b = \frac{1}{m_b}(-F_{fr} - F_{rr} - F_{fl} - F_{rl} + F_a) \tag{1}$$

$$\ddot{\theta} = \frac{1}{I_{yy}}(l_f F_{fr} + l_f F_{fl} - l_r F_{rr} - l_r F_{rl} - l_f F_{afr} + l_r F_{arr} - l_f F_{afl} + l_r F_{arl}) \tag{2}$$

$$\ddot{\phi} = \frac{1}{I_{xx}}(-b_l F_{fr} + b_r F_{fl} - b_l F_{rr} + b_r F_{rl} + b_l F_{afr} + b_l F_{arr} - b_r F_{afl} - b_r F_{arl}) \tag{3}$$

$$z_{ufr}'' = \frac{1}{m_{ufr}}(F_{fr} - F_{wfr} - F_{afr}) \tag{4}$$

$$z_{urr}'' = \frac{1}{m_{urr}}(F_{rr} - F_{wrr} - F_{arr}) \tag{5}$$

$$z_{ufl}'' = \frac{1}{m_{ufl}}(F_{fl} - F_{wfl} - F_{afl}) \tag{6}$$

$$z_{url}'' = \frac{1}{m_{url}}(F_{rl} - F_{wrl} - F_{arl}) \tag{7}$$

Considering:

$$F_{fr} = k_{fr}(z_b - l_f sin\theta + b_l sin\Phi - z_{ufr}) + c_{fr}(\acute{z}_b - l_f \theta cos\theta + b_l \Phi cos\Phi - \acute{z}_{ufr}) \tag{8}$$

$$F_{rr} = k_{rr}(z_b + l_r sin\theta + b_l sin\Phi - z_{urr}) + c_{rr}(\acute{z}_b + l_r \theta cos\theta + b_l \Phi cos\Phi - \acute{z}_{urr}) \tag{9}$$

$$F_{fl} = k_{fl}(z_b - l_f sin\theta - b_r sin\Phi - z_{ufl}) + c_{fl}(\acute{z}_b - l_f \theta cos\theta - b_r \Phi cos\Phi - \acute{z}_{ufl}) \tag{10}$$

$$F_{rl} = k_{rl}(z_b + l_r sin\theta + b_r sin\Phi - z_{url}) + c_{rl}(\acute{z}_b + l_r \theta cos\theta + b_r \Phi cos\Phi - \acute{z}_{url}) \tag{11}$$

$$F_{wfr} = k_{tfr}(z_{ufr} - z_{rfr}) \quad (12)$$
$$F_{wrr} = k_{trr}(z_{urr} - z_{rrr}) \quad (13)$$
$$F_{wfl} = k_{tfl}(z_{ufl} - z_{rfl}) \quad (14)$$
$$F_{wrl} = k_{trl}(z_{url} - z_{rrl}) \quad (15)$$

The parameters used for our model are shown in Table 2. The spring stiffness of both designs was provided by the company that made their contributions to the re-design of the vehicle. The other parameters were measured using a CAD model of the vehicle in Solidworks.

Parameter	Off-The-Shelf Design	Campus Pilot Design	New Design
Front Spring stiffness (N/mm)	14	19	21
Rear Spring stiffness (N/mm)	28	22	24
Roll axis Moment of Inertia (kg-m^2)	276.70	347.34	363.00
Pitch axis Moment of Inertia (kg-m^2)	1346.36	2095.56	2139.92
Sprung mass (kg)	1000	1065	1115
Unsprung mass (kg)	20	20	20
Front Tire- CG Distance (m)	0.81	1.14	1.25
Rear Tire- CG Distance (m)	0.81	1.14	1.25
Left Tire- CG Distance (m)	0.56	0.56	0.6
Right Tire- CG Distance (m)	0.56	0.56	0.6

Table 2. Parameters for modeling and simulation software

3.4.2 Generated inputs

For our analysis, we used three inputs to the system. A step input was used to analyze the behavior of the vehicle when a vertical displacement on the tires is exerted and maintained at 0.05m. A rectangular pulse is also used in our analysis to view the response of the system when a vertical displacement is inputted and then goes back to zero. In both previous cases, the roll angle was very small, and we couldn't appreciate the change in the roll angle. This is due to the inputs on the front tires occurring simultaneously and the moment of inertia of the vehicle. Hence, a sine input was created to visualize better the response of the vehicle's roll angle. The sine input was delayed by 90 degrees between the right and left tire in order to create a rolling motion on the vehicle. It is important to note that the rear tire inputs are delayed because of the wheelbase, and it occurs at a different time for each model. The assumed vehicle speed was 5 mph because, in the project, the vehicle was restricted to walking speed for safety reasons. The three generated inputs are shown in Figures 18, 19, and 20.

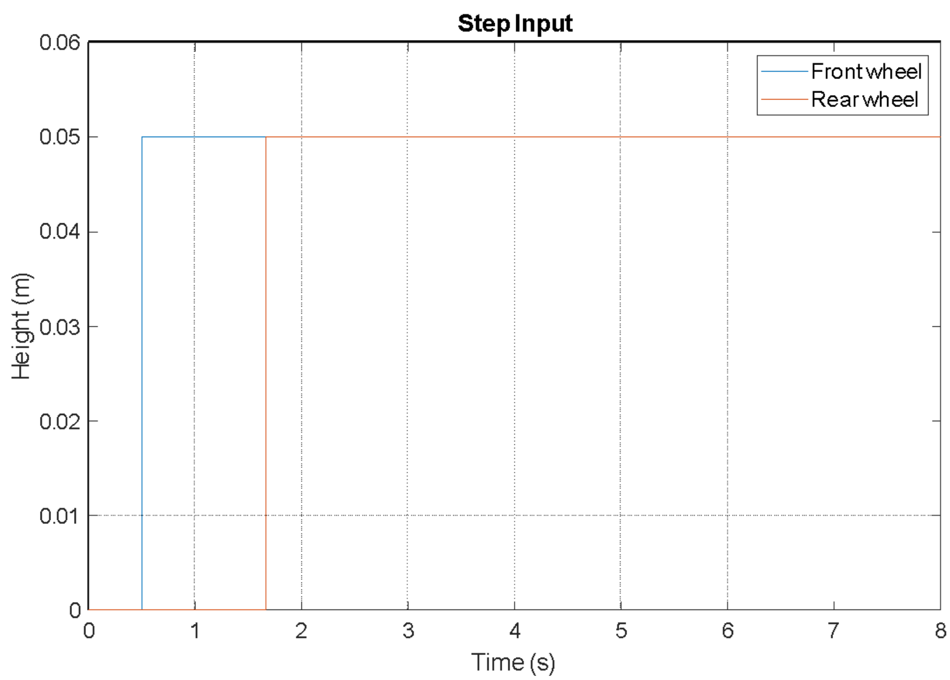


Figure 18. Step input used for the vertical dynamic analysis

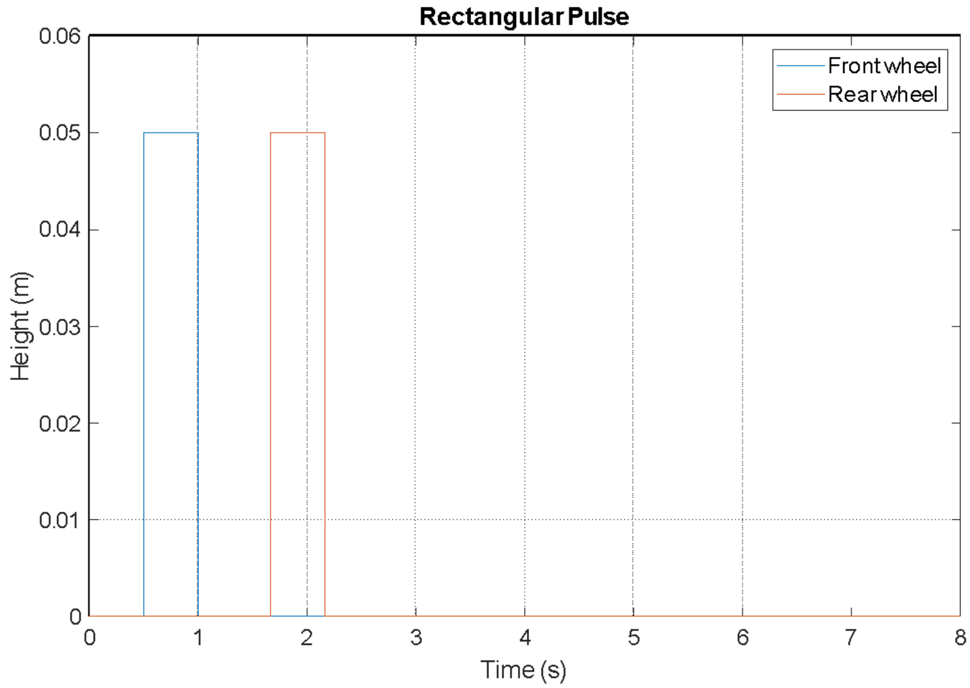


Figure 19. Rectangular pulse input for vertical dynamic analysis

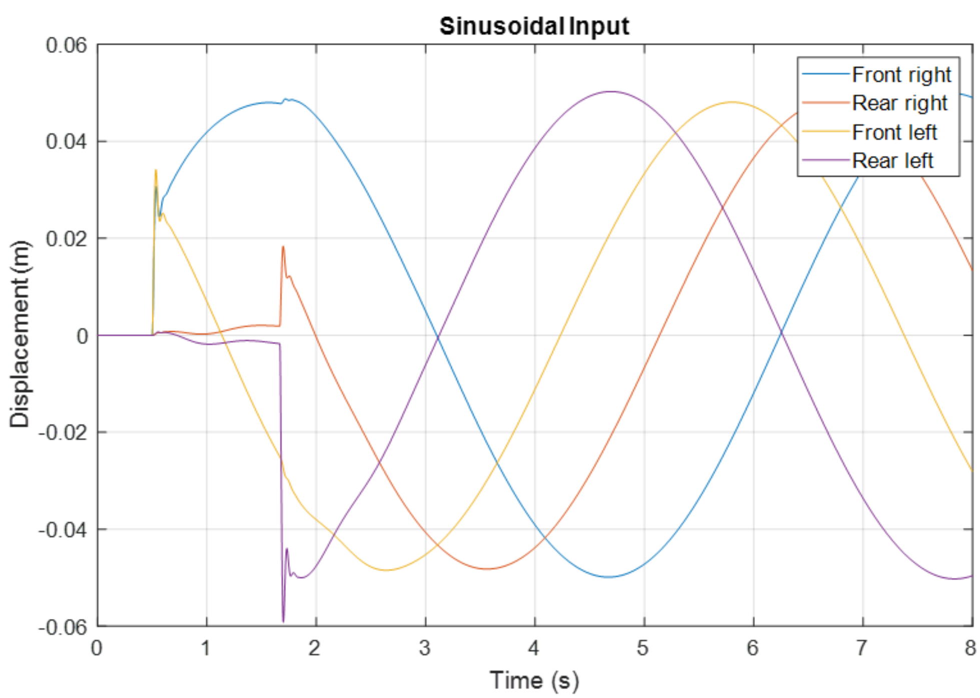


Figure 20. Sine input for roll angle

3.4.3 Control system for active suspension

The mathematical model and the control system for the active suspension system were developed in Simulink in order to minimize the vehicle's vertical acceleration. Since each suspension is independent, it can be treated as a quarter car model; therefore, we have a control system for each suspension. The acceleration of the vehicle at four different points was measured and used as our control variable. Since we want to minimize the acceleration, a reference of zero was used for our control system. The proposed system is shown in Figure 21. We used the skyhook damping theory in our control system to create a damping force between the chassis and the tire.

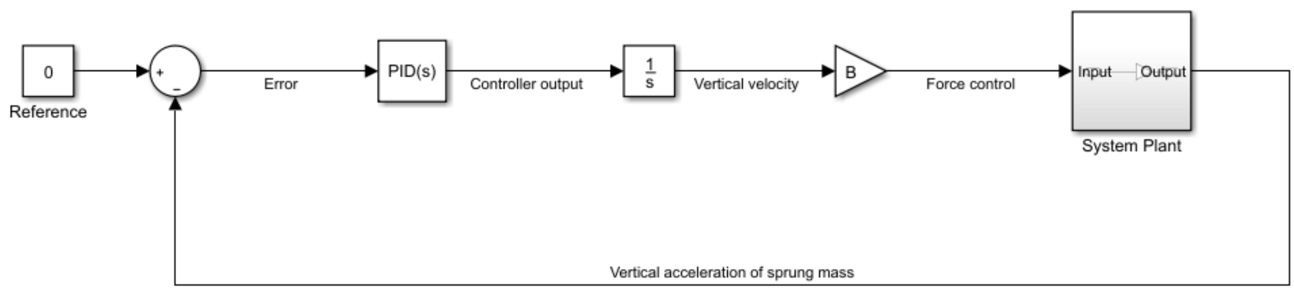


Figure 21. Control system for active suspension of quarter car model

3.4.4 ADAMS Model

An ADAMS (Automated Dynamic Analysis of Mechanical Systems, CA) model was developed to analyze the vehicle's behavior during cornering and ride comfort. The previously derived mathematical model gives us a good understanding of a vehicle's vertical dynamics, but it is based on several assumptions for simplicity. ADAMS gives us a very good approximation of a vehicle's kinematics because you can add the appropriate joints connecting two rigid bodies. Our ADAMS model was built based on pictures of the suspension geometry of the off-the-shelf design. The pictures were imported into Solidworks, and the points of the joints were measured taking the middle point between the tire and the road as a reference. The steering geometry was developed by drawing an imaginary line between the ball joint of the upper and lower control arm and offsetting 100mm towards the rear axle. This offset was approximated by measuring it on the real vehicle. Figure 22 shows our ADAMS model with and without the CAD model created in Solidworks.

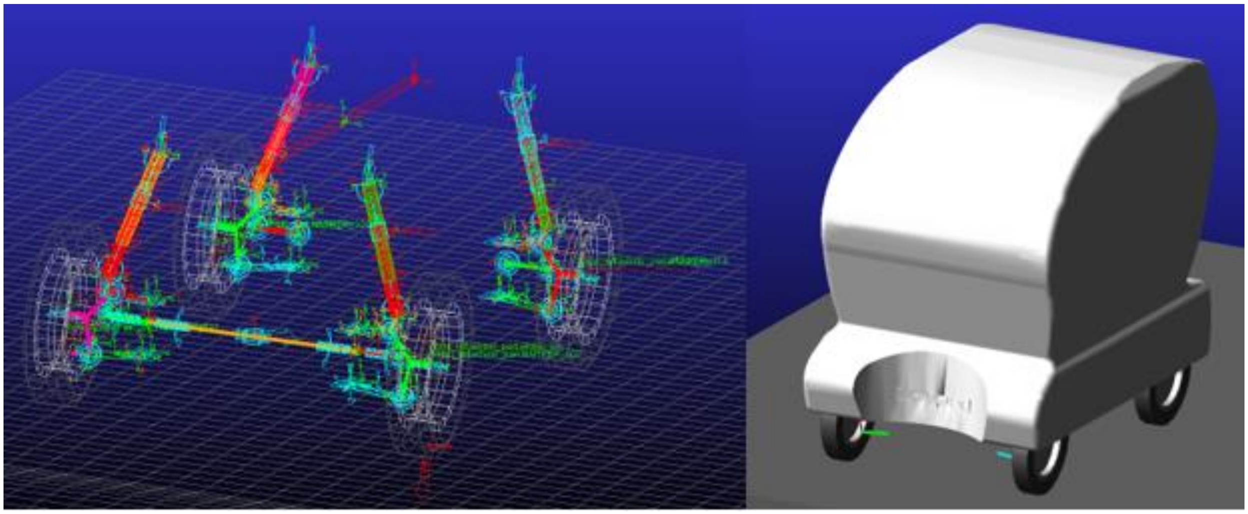


Figure 22. ADAMS model with CAD model

3.5 Steering system

A vehicle's steering system is a group of components whose function is to keep the vehicle in the desired path. This system transforms a rotational input from the driver to a translation movement to the steering rack. It is composed of steering linkages, ball joints, rack, and pinion, etc. The steering geometry varies depending on the design and the specifications you want to achieve. The rack and pinion steering system has widely grown during the past years because of the reduced complexity and easy accommodations to the front wheel system. All steering systems have tried to approximate their kinematic behavior with Ackermann's steering geometry. Ackermann's steering geometry has a trapezoidal shape, and it causes no slip angle when handling (ideal case). In this steering system, the inner wheel has a greater steer angle than the outer wheel (see Figure 23).

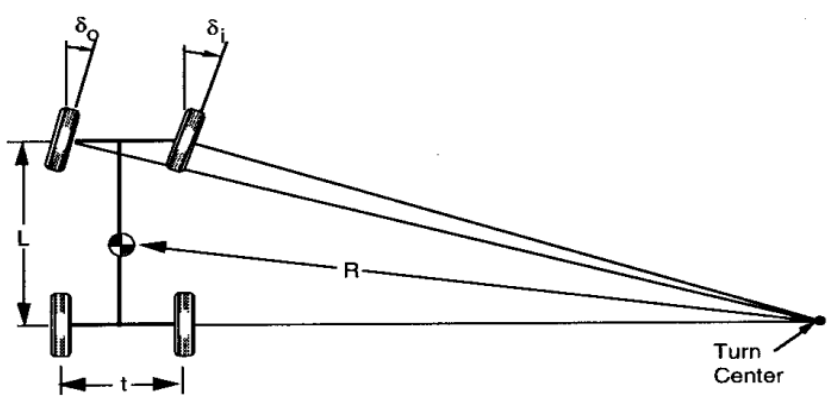


Figure 23. Ackermann turning geometry

By analyzing the triangles, we can obtain the following equations for the steering angles of the inner and outer wheel:

$$\delta_o = arctan(\frac{L}{(R+\frac{t}{2})}) = \frac{L}{(R+\frac{t}{2})} \quad (16)$$

$$\delta_i = arctan(\frac{L}{(R-\frac{t}{2})}) = \frac{L}{(R-\frac{t}{2})} \quad (17)$$

As we can see from the previous equations, the steering angle of the inner and outer wheel depends upon the wheelbase, track, and the location of the center of mass of the vehicle. These equations can also be used for the dynamics of a low speed turning vehicle in which no slip angle is assumed. Since the maximum speed of the autonomous shuttle is 15mph but was restricted to walking speed for the project, for cornering situations, a low speed turning kinematic behavior was assumed for our analysis.

3.5.1 Turning radius

The turning radius is the minimum radius required by a vehicle in a U-turn and is measured from the center of the turning circle to the outer wheel of the vehicle. The turning radius depends upon the wheelbase (distance between the front and rear wheel), track (distance between the two wheels of the same axle), and the steering angle of the outer wheel while performing the U-turn. There are many ways to calculate the turning radius, and several equations can vary depending on the amount of available information [50].

3.6 Energy consumption analysis

An analysis of energy consumption was performed using the Autonomie modeling software. Autonomie is a fuel economy modeling software developed by Argonne National Labs to perform vehicle energy consumption and performance analysis. Autonomie was used to determine the operating range of each shuttle design. The battery pack for each design is shown in Table 3. The off-the-shelf design has a 6 x 8V lead-acid battery pack in series, and the campus pilot design has a 4 x 12V lithium iron phosphate battery pack in series. The selected battery configuration for the new design is a 6 x 12V lithium iron phosphate battery pack in series. The number of batteries in series was increased because we are assuming we have no space limitations like in the campus pilot design. Also, we chose the 12V battery because we wanted to use a battery with a similar energy capacity per battery. Lithium iron phosphate was selected over lead-acid batteries because of the following reasons:

- Lithium iron phosphate batteries have a longer lifespan than lead-acid batteries
- Lithium iron phosphate batteries are lighter than lead-acid batteries
- Lithium iron phosphate batteries are safer than lithium-ion batteries
- Lithium iron phosphate batteries are less susceptible to problems when discharging than lead-acid batteries

	Off-the-shelf design	Campus pilot design	New design
Battery configuration	6 x 8V lead-acid battery pack in series	4 x 12V lithium iron phosphate battery pack in series	6 x 12V lithium iron phosphate battery pack in series

Table 3. Battery configuration of the three shuttle designs

Autonomie is a simulation tool based on MATLAB and Simulink with a library of preloaded vehicle models (e.g., electric, internal combustion engines, fuel cell electric vehicles, hybrid and plug-in hybrids) and drives cycles that can be used to perform energy consumption analysis of user-selected vehicle models and custom drive cycles.

The parameters of a preloaded electric vehicle model in Autonomie were matched to the specifications of our three autonomous shuttle designs. Some of the simulation parameters are shown in Table 4. For increased fidelity/realism, this analysis used a custom drive cycle with a route matched to the intended service route on Western Michigan University's campus. The drive cycle was developed using an ELM327 connected to the Controller Area Network (CAN) bus through the OBDII port on a research vehicle driven around the Western Michigan University's main campus (shown in Figure 24).

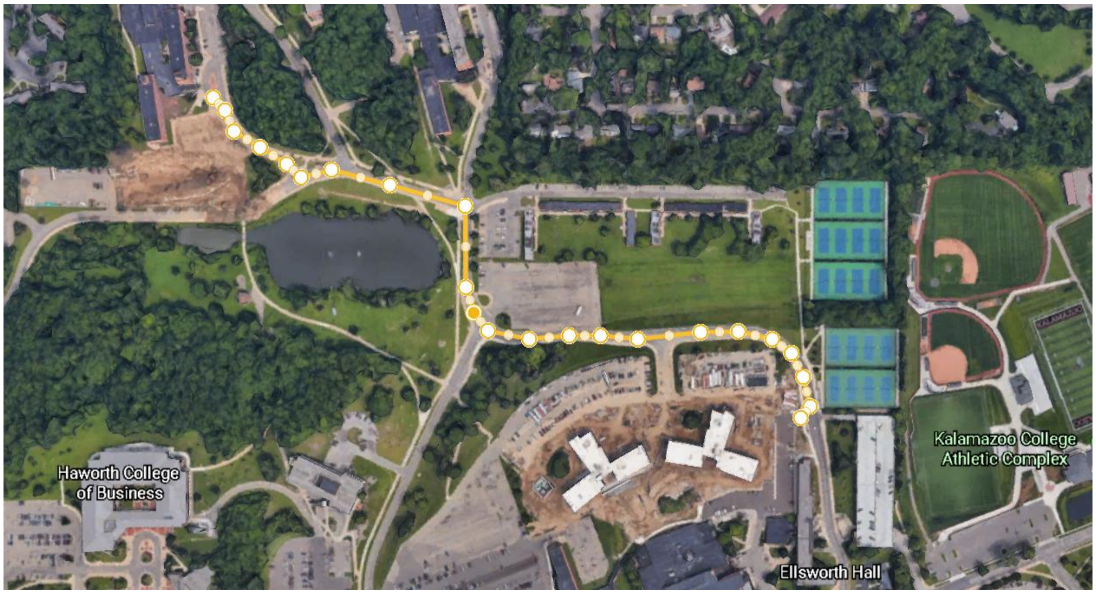


Figure 24. Route driven to create custom drive cycle

The velocity vs. time data was recorded and appended in series to create a drive cycle sufficiently long enough to exhaust the vehicle battery fully. This route was chosen because it matches the one driven by the autonomous shuttles. The downhill and uphill grade is approximately 3 degrees. The elevation of the driven route was approximated using Google Earth. The custom drive cycle is shown in Figure 25.

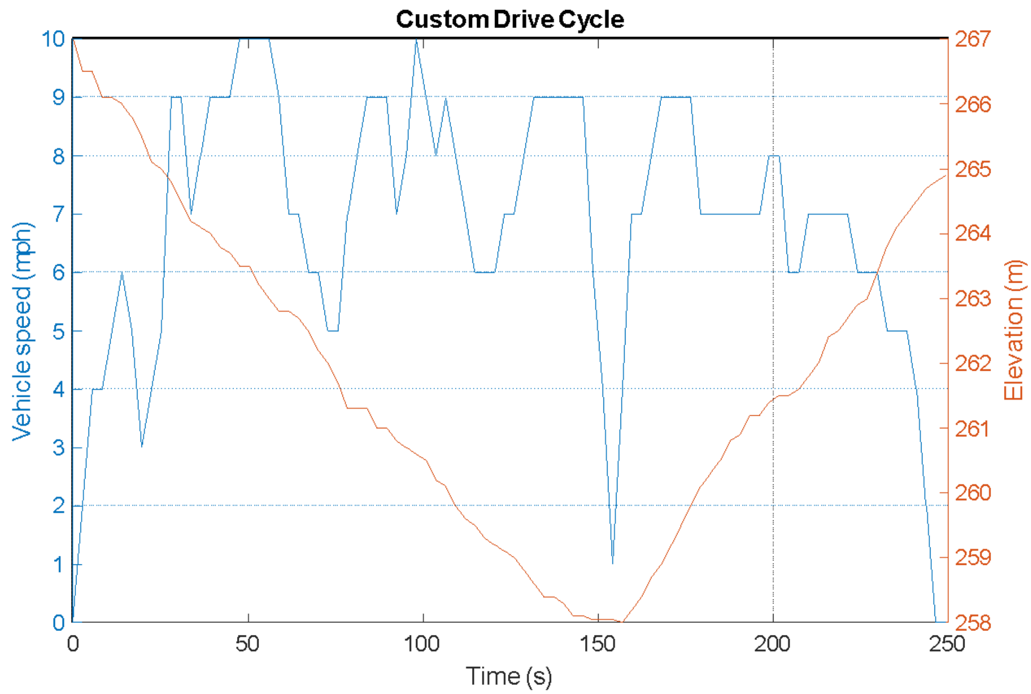


Figure 25. Velocity vs time recorded for custom drive cycle

This custom drive cycle was then used as an input into the energy consumption model in Autonomie. Two model outputs were obtained:

- **Vehicle Range**: The vehicle range is calculated as the total distance traveled per charge [51]. The range of an electric vehicle may depend upon the size of the battery, the speed of the vehicle, aerodynamics, road conditions, the drive cycle, temperature, etc. We evaluate vehicle range using the rigorously validated vehicle models that come pre-loaded in the Autonomie modeling software.

- **Time to discharge:** The time to discharge is calculated to determine how long the battery will sustain a charge while operating at max speed. Factors that affect discharge time include battery size, vehicle speed, surface incline, motor power, etc.

Parameter	Off-The-Shel Design	Campus Pilot Design	New Design
Rolling resistance	0.008	0.008	0.008
Drag coefficient	0.311	0.311	0.34
Capacity amps-Hours (Ah)	176 (100 Hrs.)	110 (20 Hrs.)	167 (100 Hrs.)
Energy capacity per battery (kWh)	1.5	1.2	1.4
Voltage (V)	48	48	48
Horsepower (kW)	3.3	3.3	3.3
Min SOC (%)	5	5	5
Front area of the vehicle (m^2)	2.372	2.372	2.42
Rear axle ratio	14.76:1	14.76:1	14.73:1

Table 4. Parameters used for Autonomie simulation software

3.7 Cost analysis

A brief cost model was developed in order to give a contrast to the implications of considering accessibility as an afterthought. With the estimated purchase prices shown in Table 1, the electrical consumption of the shuttles outputted from Autonomie, a cost analysis was performed with the assumptions shown in Table 5.

Parameters	Off-The-Shelf Design	Campus Pilot Design	New Design
Operator salary ($/year)	$55,000.00	$55,000.00	$55,000.00
Purchase price ($)	$85,000.00	$105,000.00	$95,000.00
Cost of active suspension system ($)	-	-	$7,000.00
Maintenance of suspension system ($/year)	-	-	$1,000.00

Maintenance per mile ($/mile)	0.03	0.03	0.03
Cost of electricity ($/kWh)	0.13	0.13	0.13
Total years	15	15	15
Total passengers per day	300	300	300
Total miles (miles/year)	9100	9400	8900
Vehicle depreciation rate first year (%)	20	20	20
Vehicle depreciation rate other years (%)	15	15	15
Interest rate (%)	5	5	5
Operator annual salary raise (%)	5	5	5
Electrical consumption (Wh/mile)	198.1	209.67	216.87

Table 5. Input for our cost model

Since a safety operator was used for WMU's campus pilot, we incorporated that in our cost model and assumed a salary of $55,000 per year and an annual raise of 5% per year. The shuttle worked on the demand; therefore, a total of 300 passengers per day was assumed for our analysis. The total number of miles per year driven by each shuttle was estimated by using the range outputted from Autonomie and assuming the shuttles operate 5 hours per day. To compare the cost of an accessible autonomous shuttle with an integrated active suspension system (new design) and previous designs, the cost of an active suspension system was added to the cost analysis.

4 Results

4.1 Ride comfort study

A ride comfort study of a passive suspension system of three autonomous shuttles was performed with the intention to compare the compromises of post-production modifications for wheelchair accessibility. This analysis was performed by submitting our previously derived mathematical model to several road inputs. Also, an active suspension model was developed and compared to the benefits of integrating this technology and the passive suspension system into the new design. Furthermore, an ADAMS/MATLAB co-simulation was performed in order to combine MATLAB's developed control system with our ADAMS model. The vertical displacement, vertical acceleration, pitch angle, and roll angle of the vehicle body were analyzed. Simulation results of our passive suspension system using the three generated inputs indicate an increasing instability due to the wheelbase increase (see Figures 26-32). The decrease in pitch and roll angle indicates an increase in stability during cornering situations and various road conditions. The decrease in vertical acceleration indicates less vibration will be exerted to the human body while riding the autonomous shuttle.

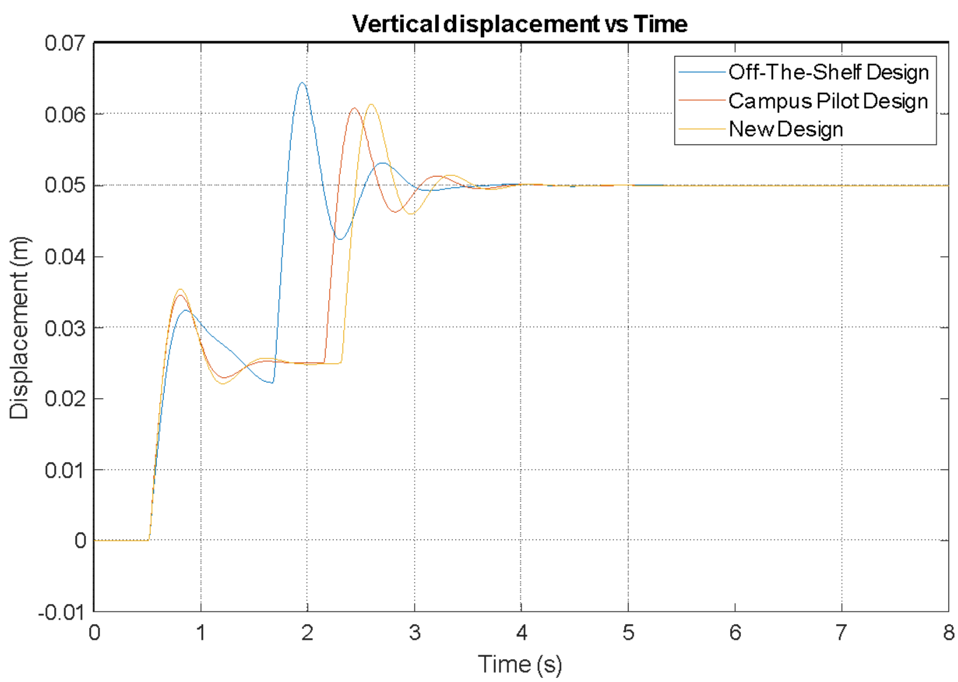


Figure 26. Vertical displacement of three shuttle designs submitted to step input

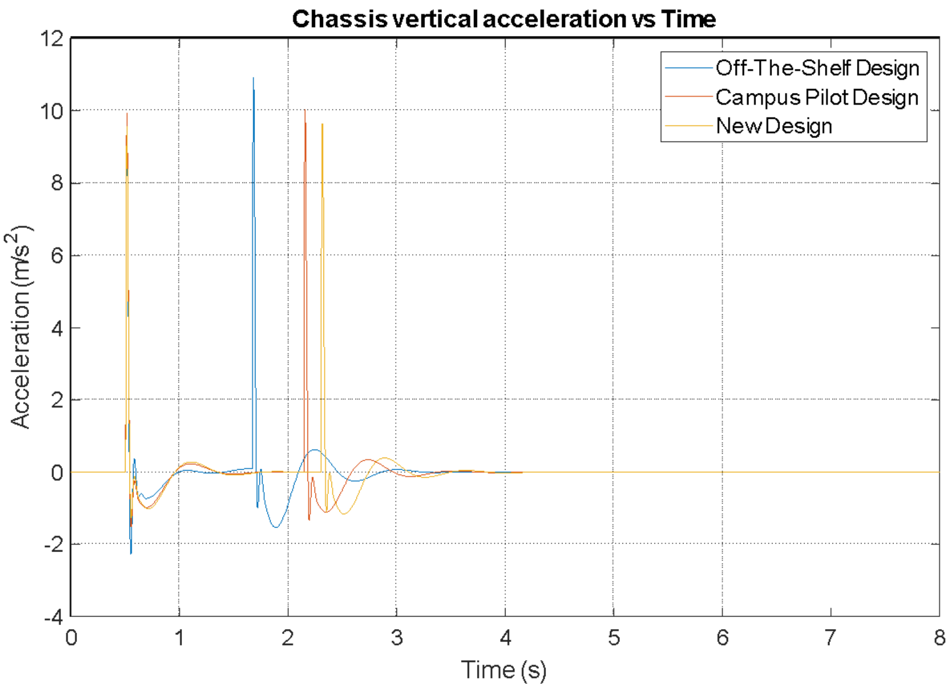


Figure 27. Vertical acceleration of three shuttle designs submitted to step input

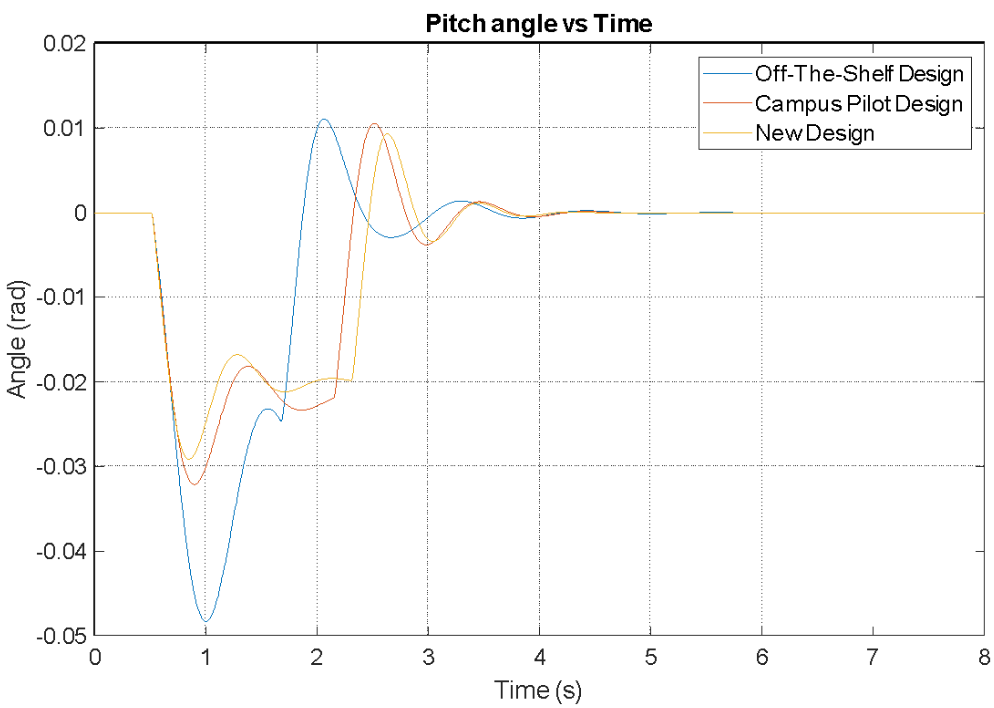


Figure 28. Pitch angle of three shuttle designs submitted to step input

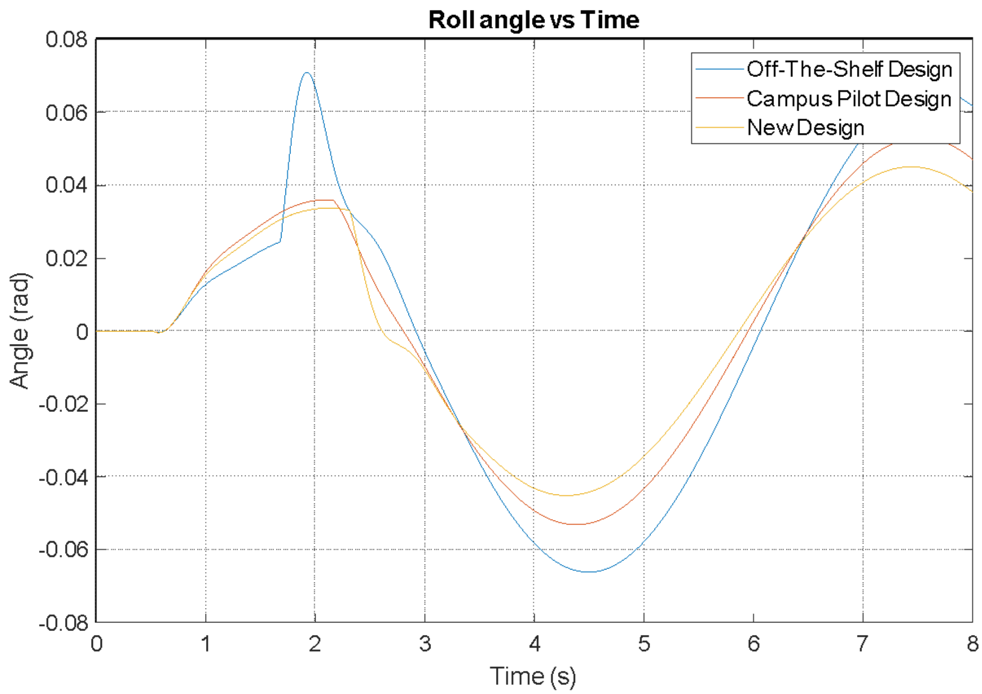


Figure 29. Roll angle of three shuttle designs submitted to sine input

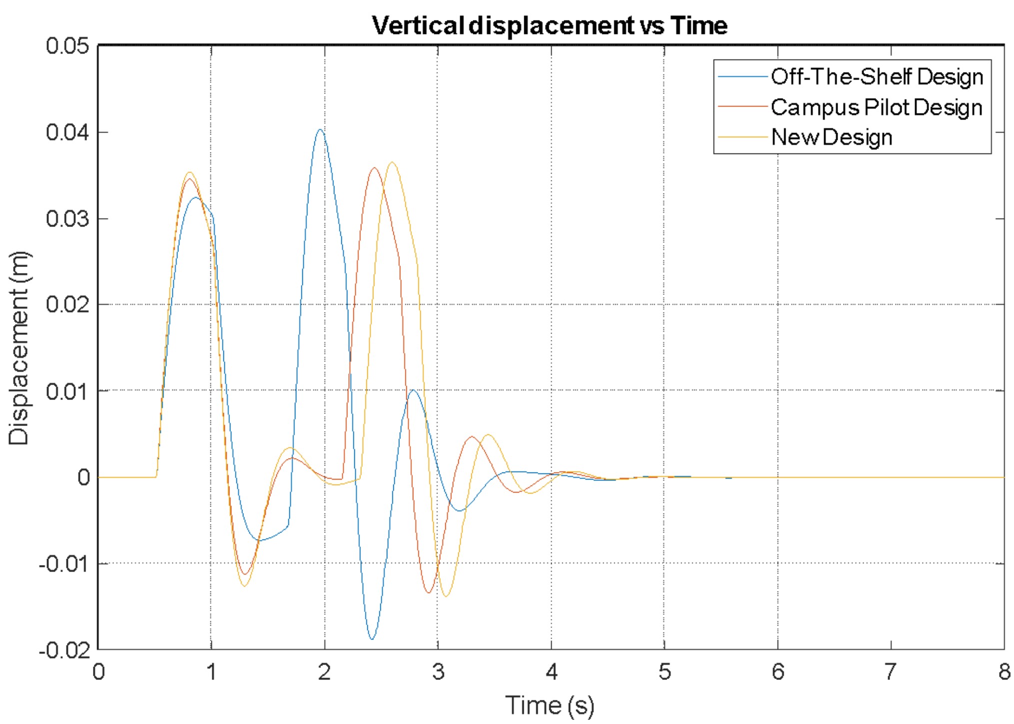


Figure 30. Vertical displacement of three shuttle designs submitted to rectangular pulse

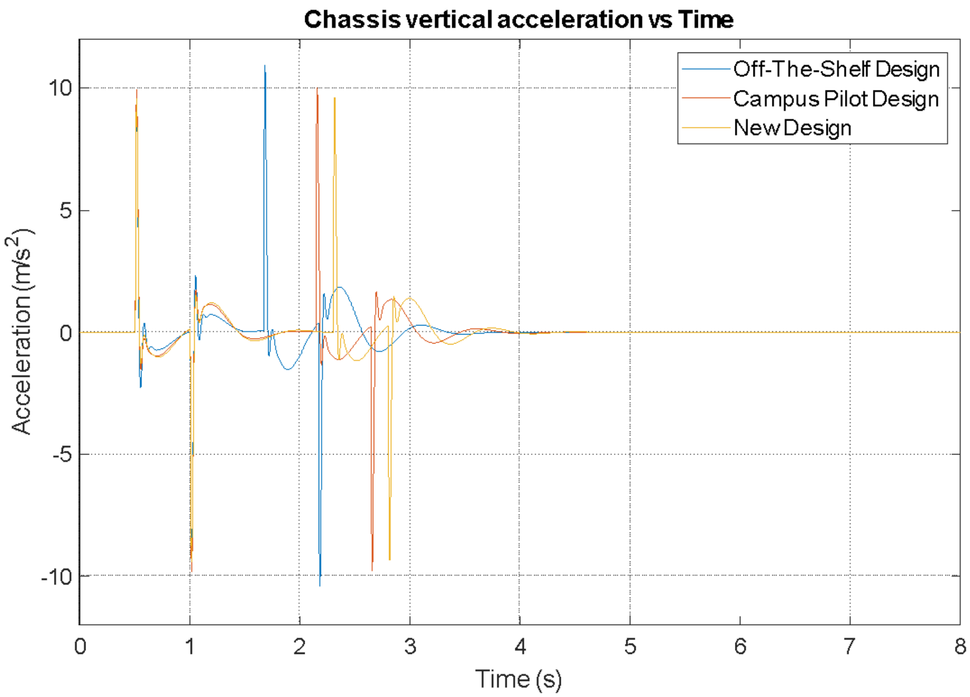


Figure 31. Vertical acceleration of three shuttle designs submitted to rectangular pulse

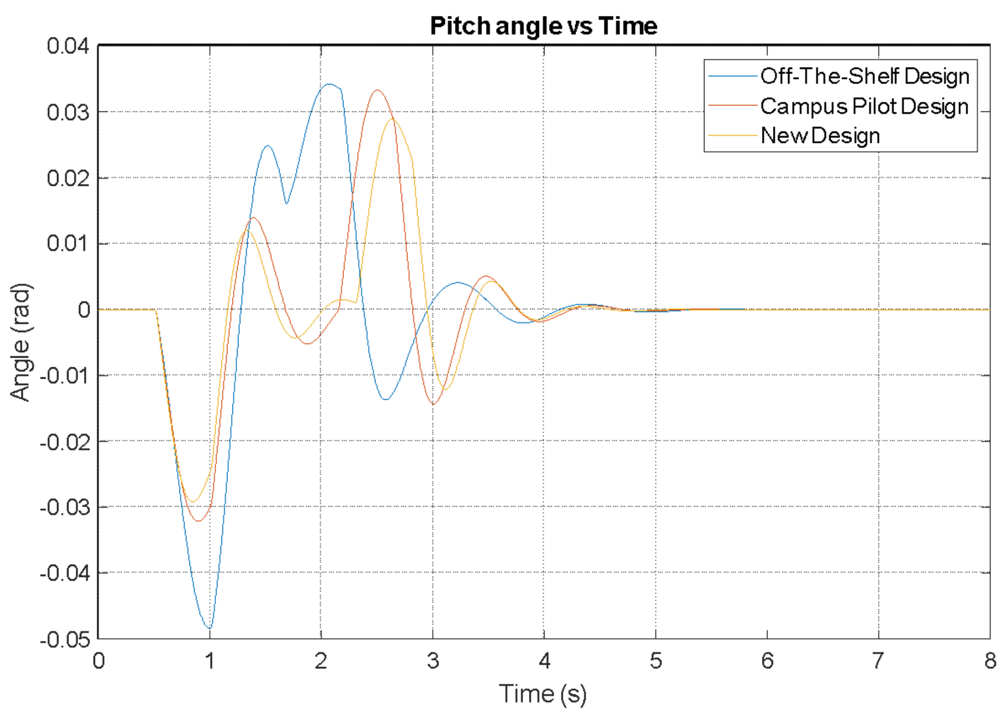


Figure 32. Pitch angle of three shuttle designs submitted to rectangular pulse

4.1.1 Active suspension analysis

From previous results, we see our new design has more stability when it encounters road disturbances, which indicates the passenger will have a smoother ride. Since some modern vehicles possess an active suspension system, our intention is to analyze the benefits of applying this system to an accessible autonomous shuttle. The developed control system is shown in Figure 33. The acceleration of the chassis was measured in each suspension and used in our feedback system. The PIDs were tuned using the trial and error method in order to minimize our control variable (chassis vertical acceleration). The PID values used for each suspension are shown in Table 6. The simulation results of the active suspension system are shown in Figures 34-40.

PID parameters	Wheel suspension system			
	Front left	Front right	Rear left	Rear right
Proportional gain (Kp)	2	2	2	2
Integral gain (Ki)	1	1	1	1
Derivative gain (Kd)	0.5	0.5	0.5	0.5

Table 6. PID values for the active control suspension system

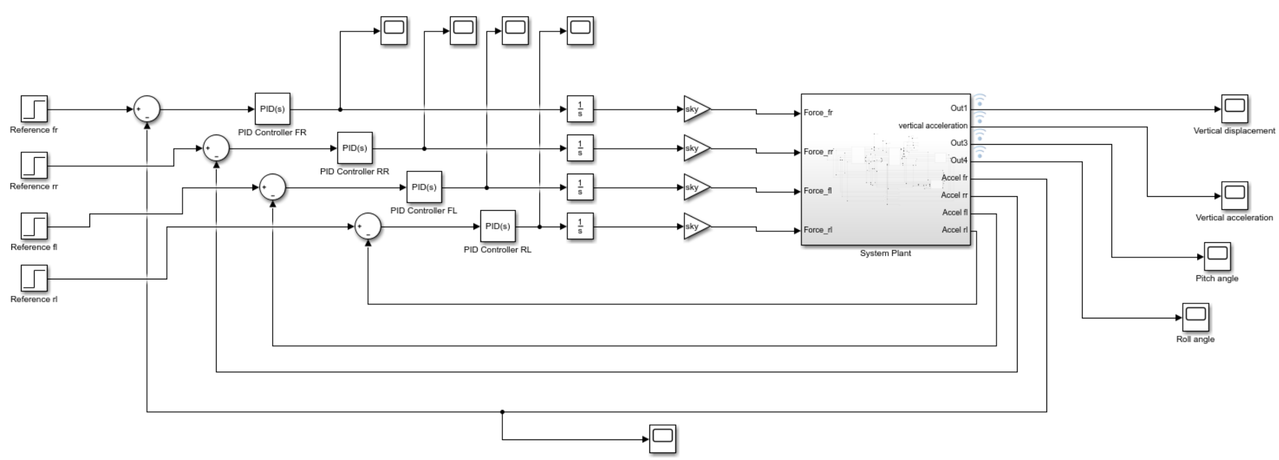


Figure 33. Control systems for active suspension system

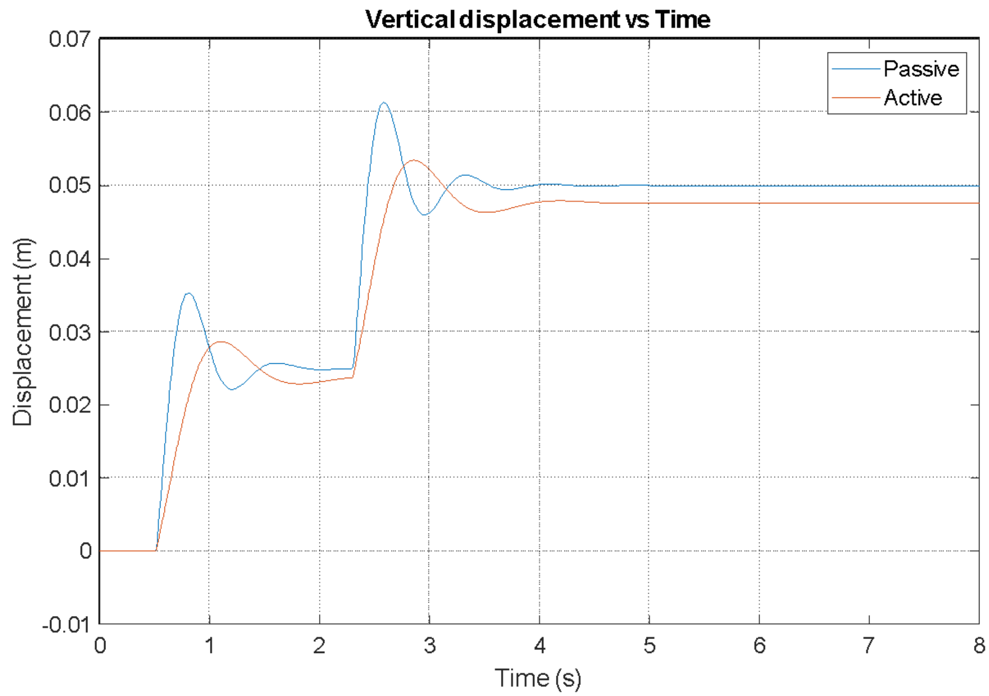


Figure 34. Vertical displacement of the new design with a passive and active suspension system submitted to step input

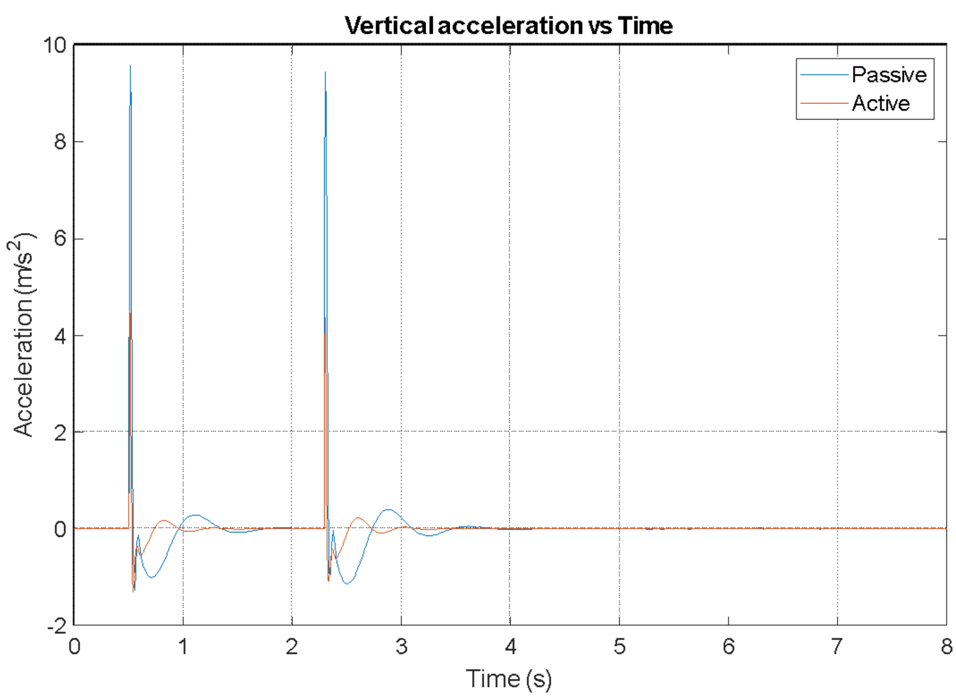


Figure 35. Vertical acceleration of the new design with a passive and active suspension system submitted to step input

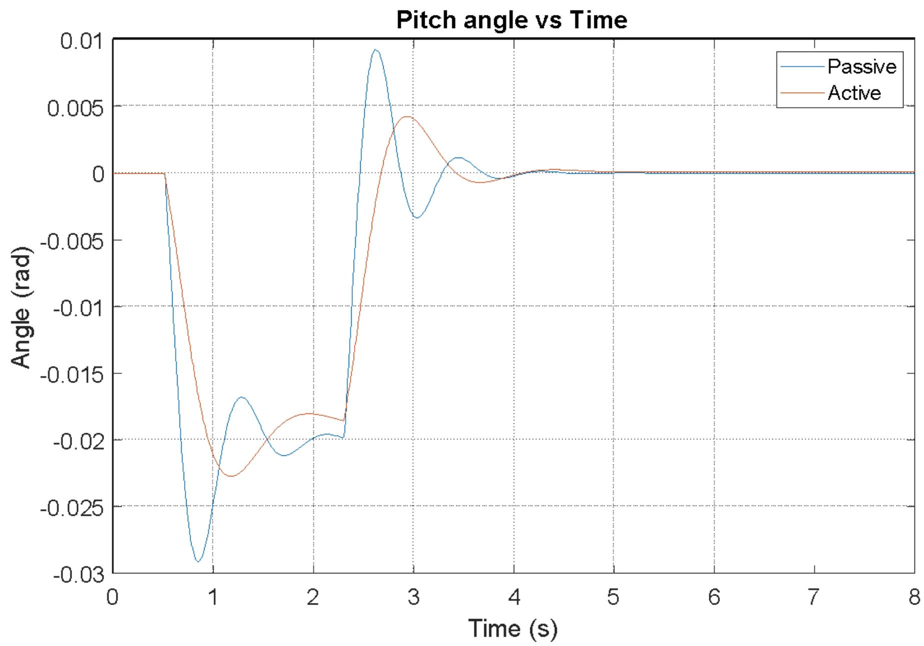


Figure 36. Pitch angle of the new design with a passive and active suspension system submitted to step input

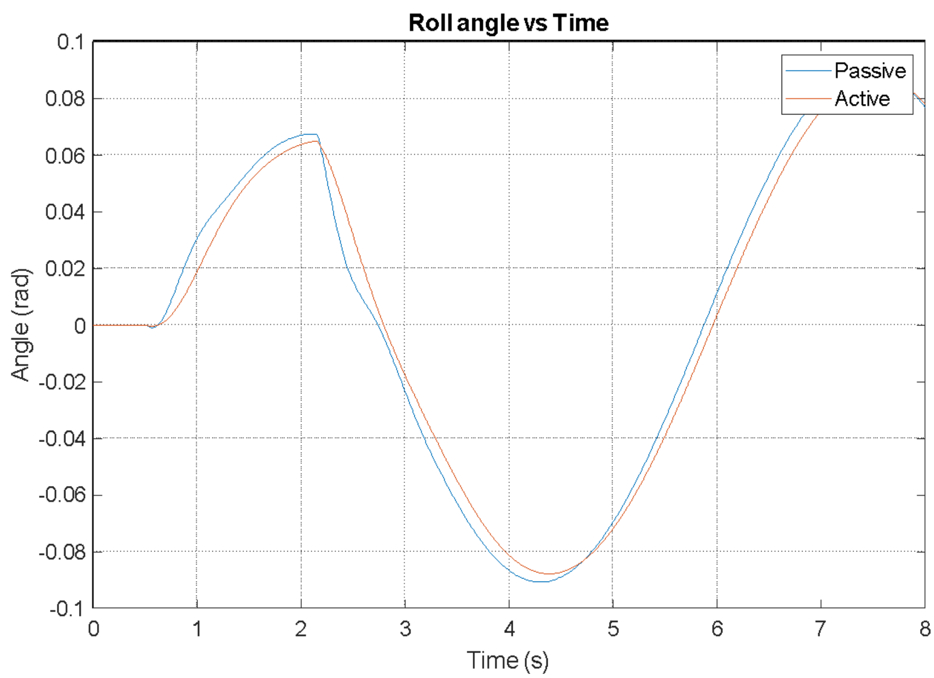


Figure 37. Roll angle of the new design with a passive and active suspension system submitted to sine input

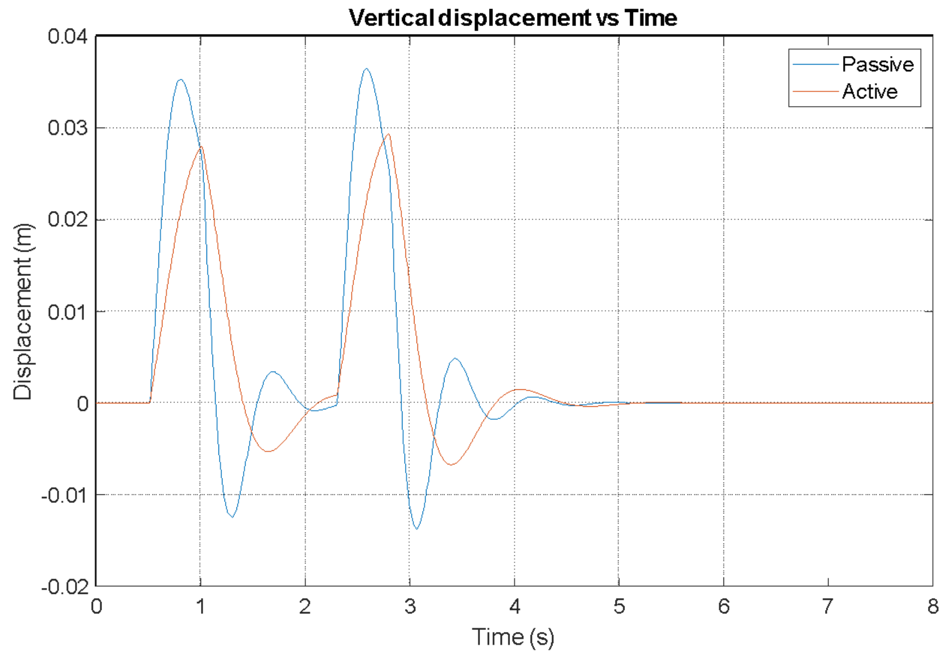


Figure 38. Vertical displacement of the new design with a passive and active suspension system submitted to rectangular pulse

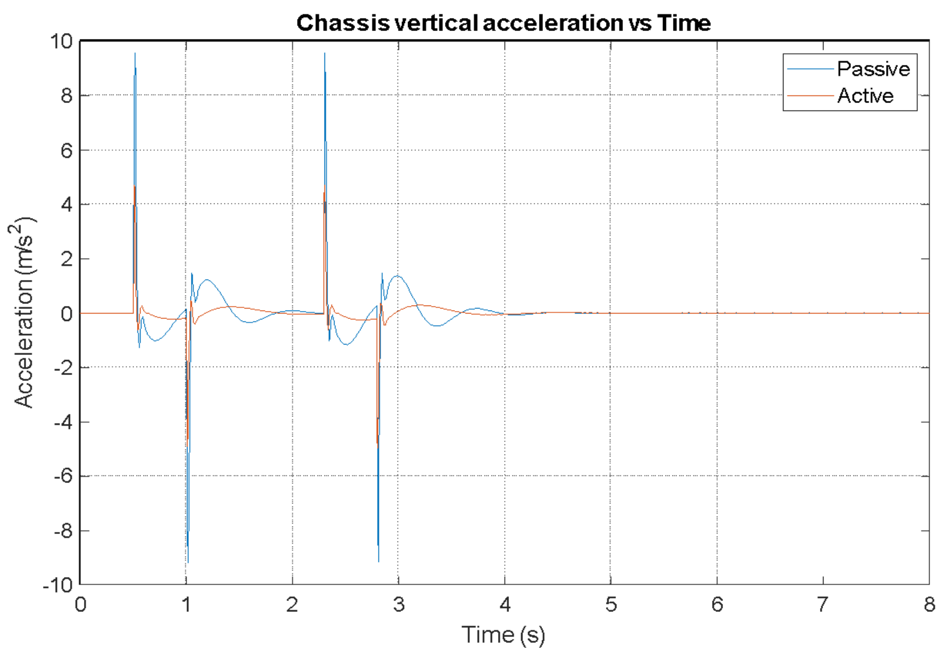


Figure 39. Vertical acceleration of the new design with a passive and active suspension system submitted to rectangular pulse

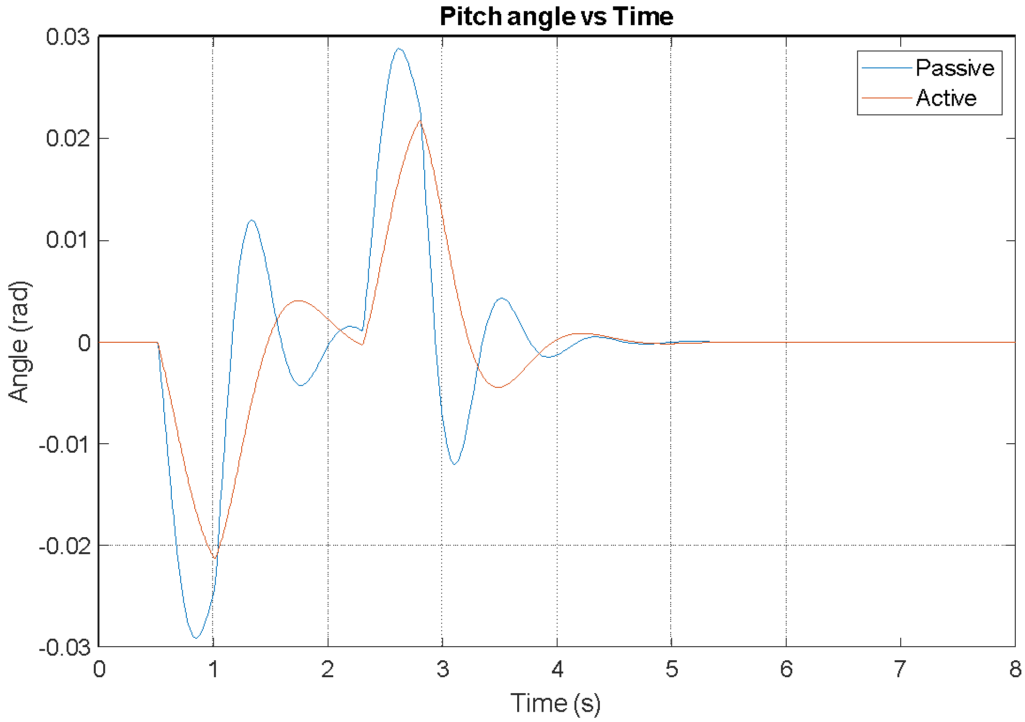


Figure 40. Pitch angle of the new design with a passive and active suspension system submitted to rectangular pulse

4.1.2 ADAMS/MATLAB Co-simulation

After validating our active suspension control systems in MATLAB, we want to implement that into the developed ADAMS model because it possesses all the kinematics of the actual autonomous shuttle. An ADAMS/MATLAB co-simulation was performed. ADAMS control toolbox was used to create an m-file and import it into MATLAB with the appropriate output and input variables. With this m-file, a Simulink block was created and used in our control system (shown in Figure 41). The output control variables from ADAMS are the vertical displacement and acceleration, pitch angle, roll angle, and the acceleration in each suspension (which are feedback into the system). For the co-simulation, we created two scenarios, (1) the shuttle going through a pothole, and (2) the shuttle driven in a sinusoidal road. Simulation results are presented in Figures 42-49.

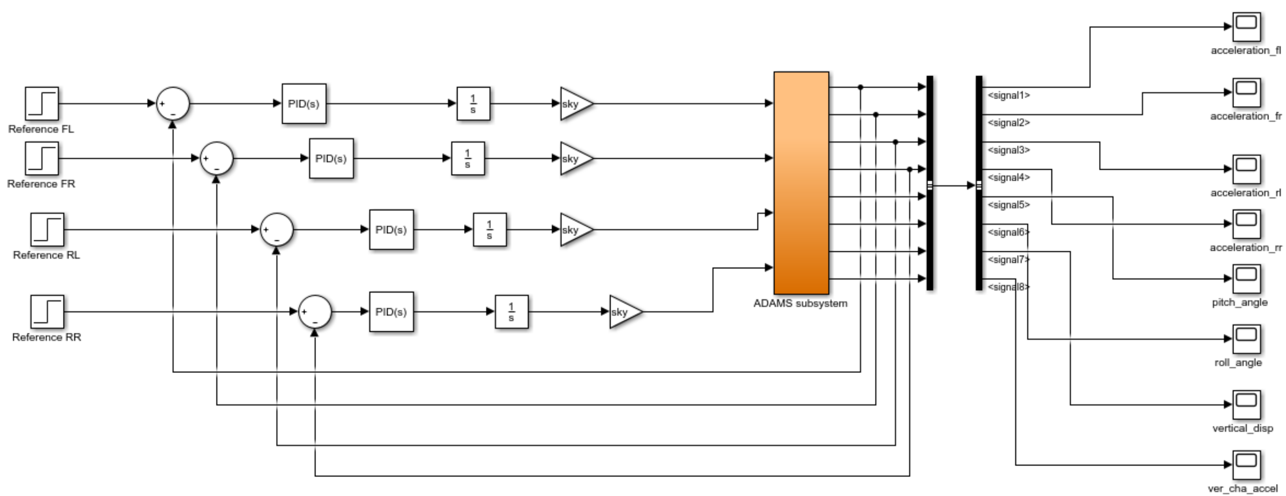


Figure 41. Control system for Co-simulation between ADAMS and MATLAB

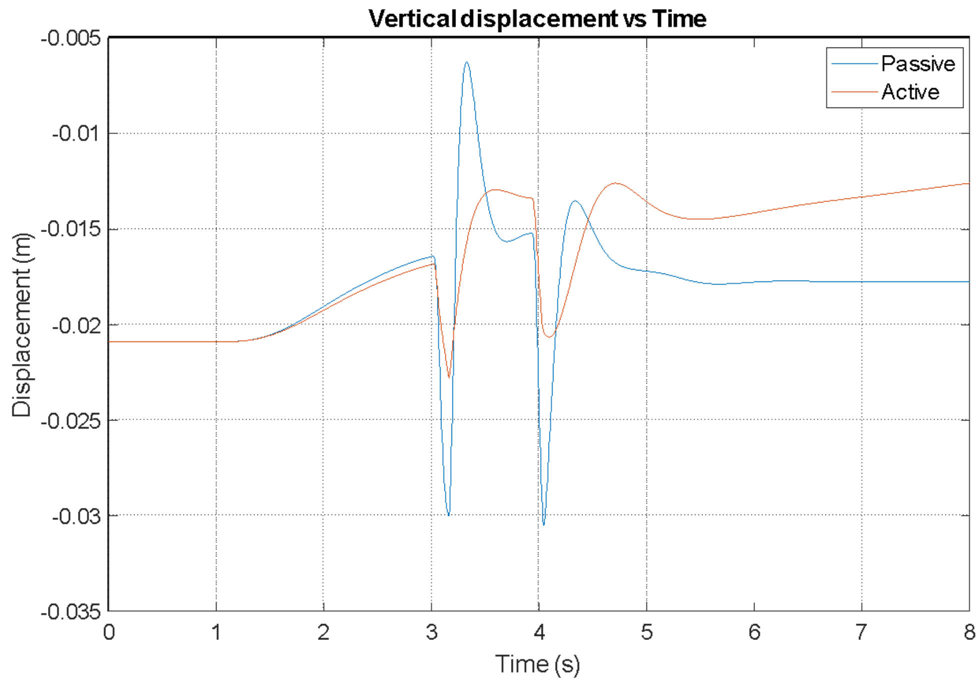


Figure 42. Vertical displacement from Co-simulation using pothole road

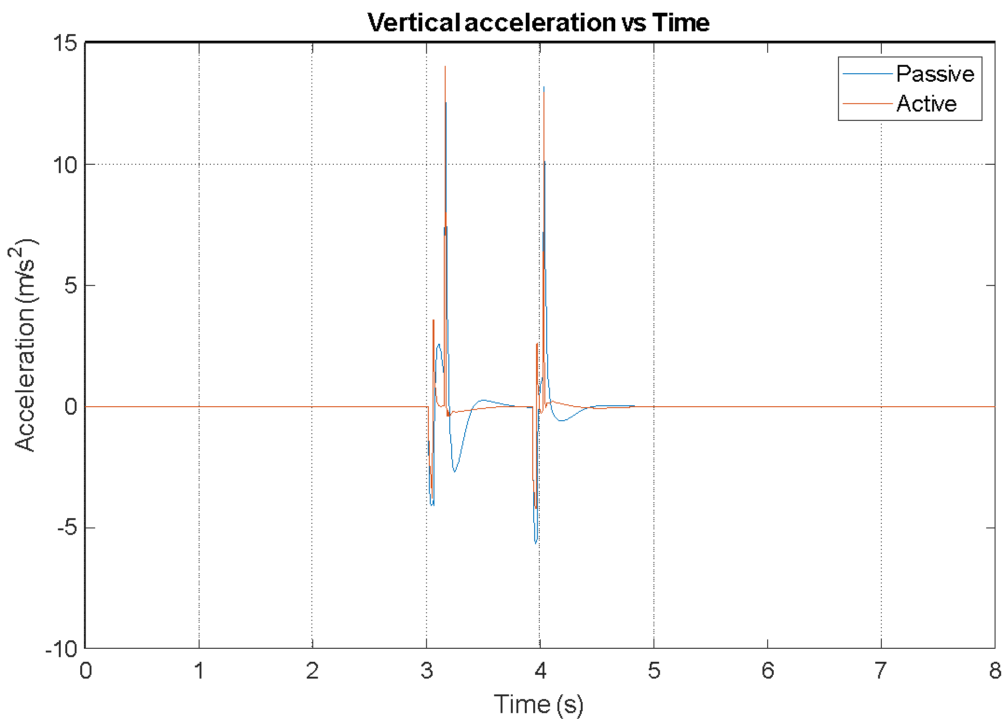


Figure 43. Vertical acceleration from Co-simulation using pothole road

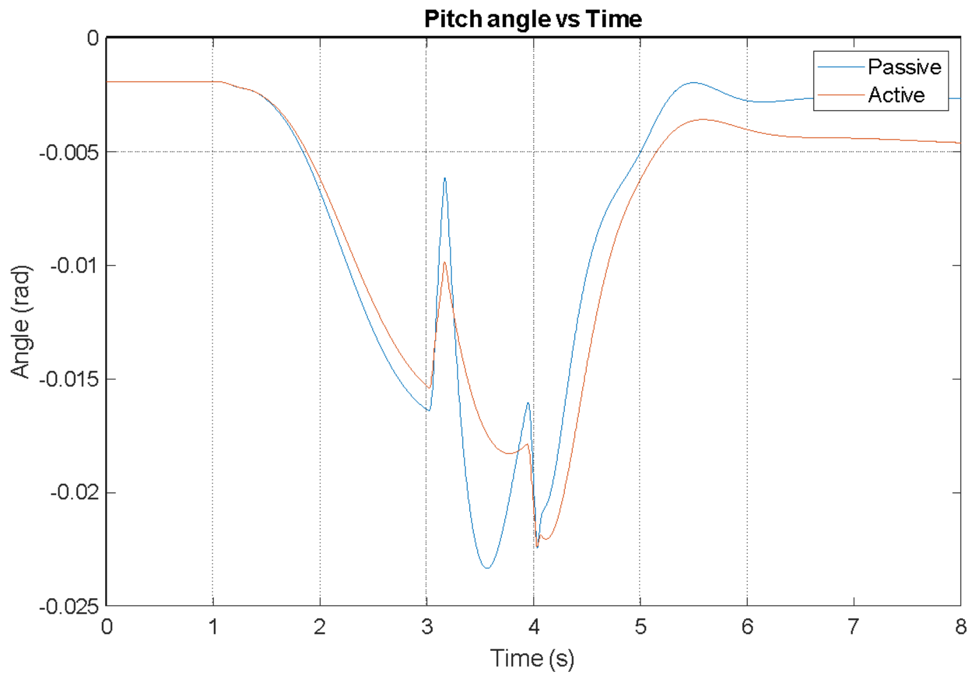


Figure 44. Pitch angle from Co-simulation using pothole road

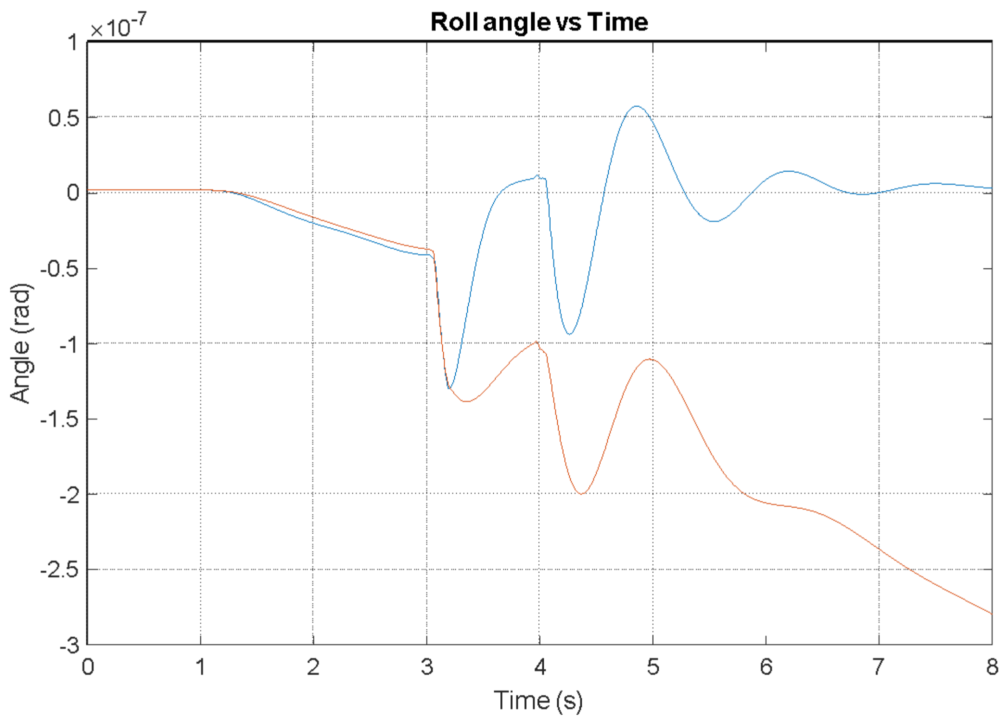


Figure 45. Roll angle from Co-simulation using pothole road

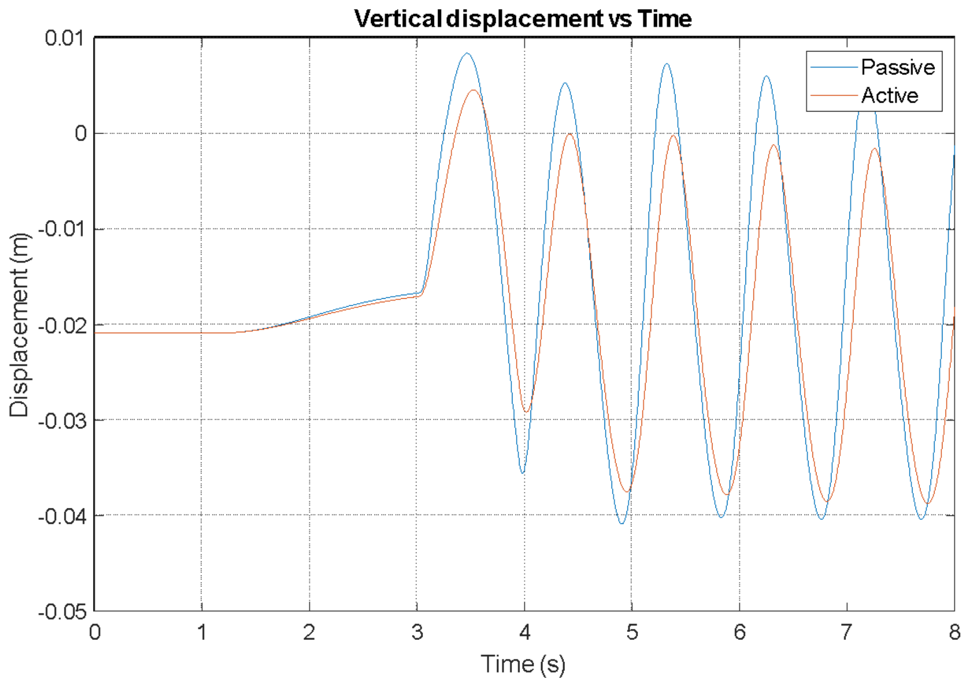


Figure 46. Vertical displacement from Co-simulation using sine road

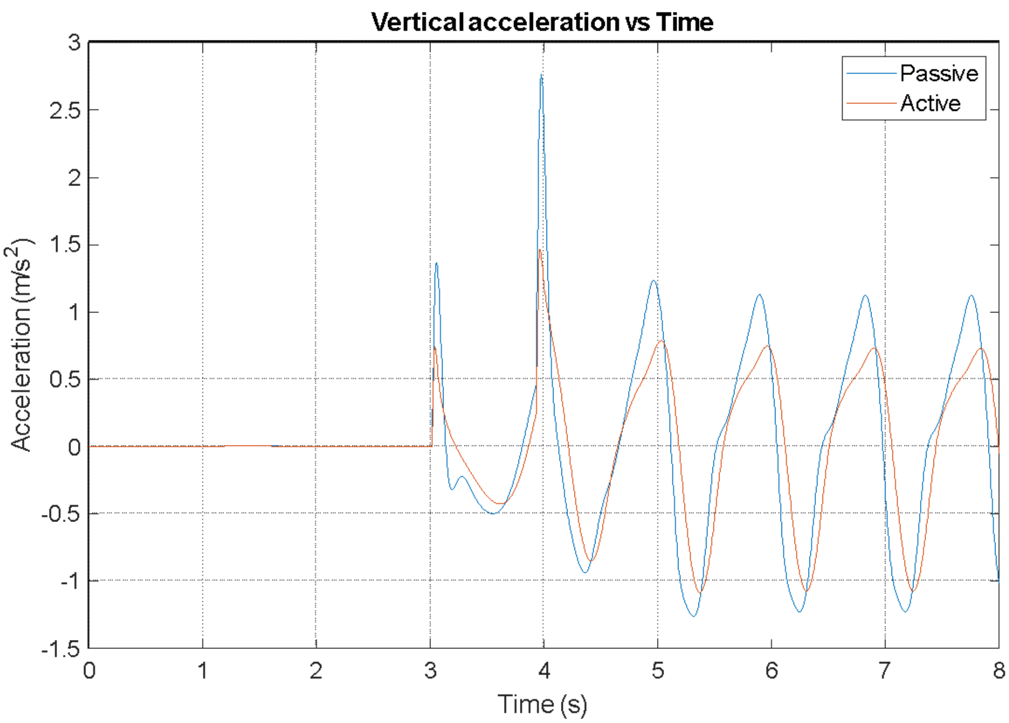


Figure 47. Vertical acceleration from Co-simulation using sine road

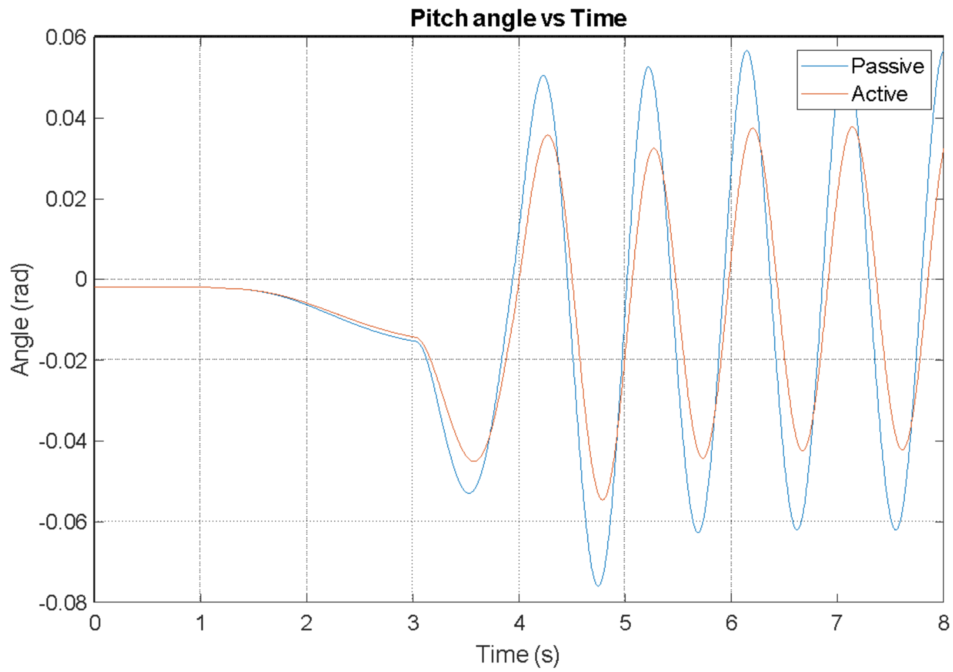


Figure 48. Pitch angle from Co-simulation using sine road

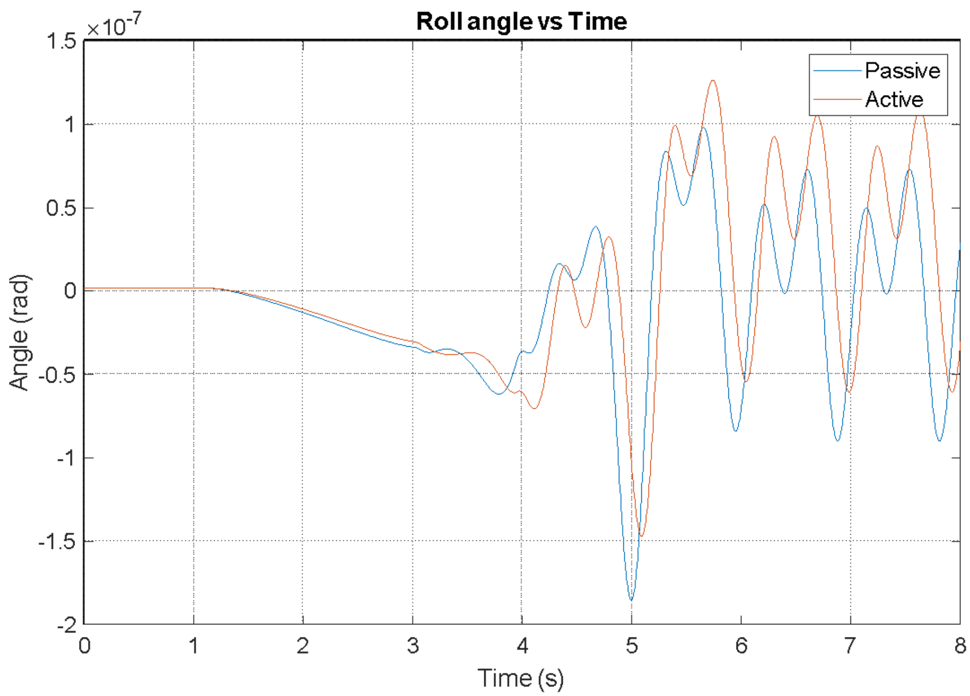


Figure 49. Roll angle from Co-simulation using sine road

4.2 Turning radius

The turning radius is also a parameter studied for this research because it represents the minimum radius a vehicle can achieve in a 180-degree turn (U-turn). This parameter tells us whether the vehicle possesses more or less maneuverability than another vehicle. The turning radius depends on the wheelbase, track, and the steering angle of the vehicle, as shown in section 2.6. Hence, since the wheelbase was increased in order to accommodate wheelchair users, we want to analyze the effects of these post-production modifications in terms of maneuverability and the performance of our new design. Since our steering geometry was an approximation and the turning radius of the off-the-shelf design was given by the manufacturer, the steering lock was determined by increasing the displacement of the steering rack until this turning radius was achieved. The steering geometry of the off-the-shelf and campus pilot design is the same; we applied the same rack displacement and measured the turning radius. On the other hand, the track of the new design was increased; therefore, it possesses a different steering geometry. To determine the turning radius for the new design, we assumed the steering angle of the right and the left wheel was the same as the other models. Even though we have the same steering angle on both wheels, the steering geometry, track, and wheelbase of the vehicle are different. The required rack displacement was measured in order to achieve that steering angle. The turning radius of the three designs is shown in Figure 50.

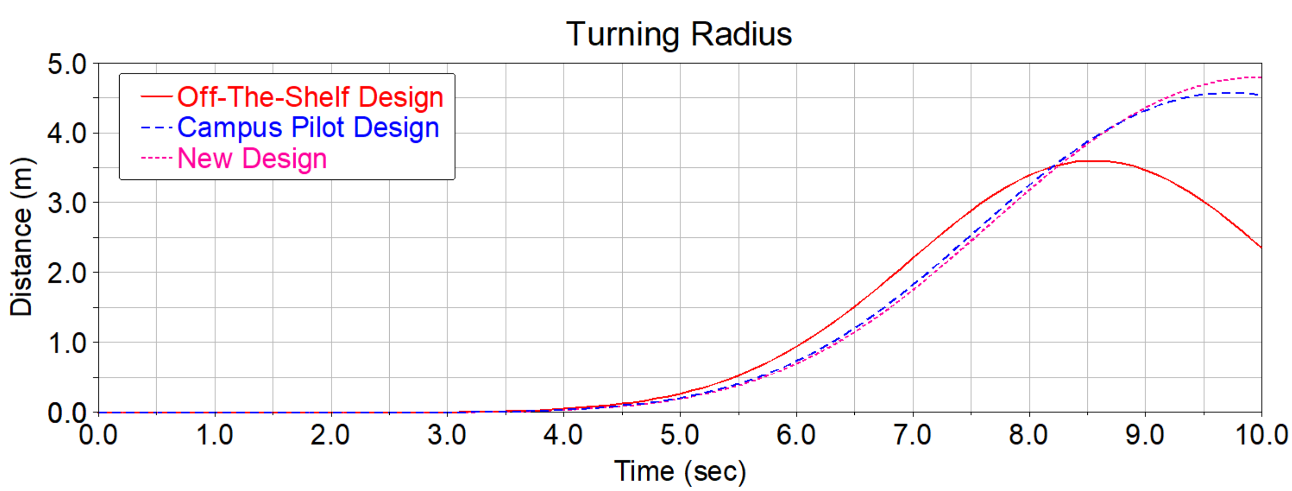


Figure 50. Turning radius of the three autonomous shuttles

4.3 Energy consumption analysis

Since the battery configuration was changed due to space limitations, an energy consumption analysis was performed to compare the operating range and time to discharge of the three electric autonomous shuttles. The off-the-shelf design, had 6 X 8V lead-acid batteries in series to obtain an energy capacity of 8kWh and battery configuration for the campus pilot design was changed to 4 X 12V lithium iron phosphate batteries in series to obtain an energy capacity of 4.8kWh. Hence, simulation results from Autonomie indicate we have a decrease in terms of operating range and time to discharge of the campus pilot design. The battery configuration of the new design was assumed to be 6 X 12 V lithium iron phosphate batteries in series to obtain an energy capacity of 8.4kWh. The SOC (State of Charge) vs. time and the total distance traveled vs. time were plotted of all three designs (see Figures 51 and 52). Both analyses were determined by using the custom drive cycle and run a simulation until the battery was exhausted.

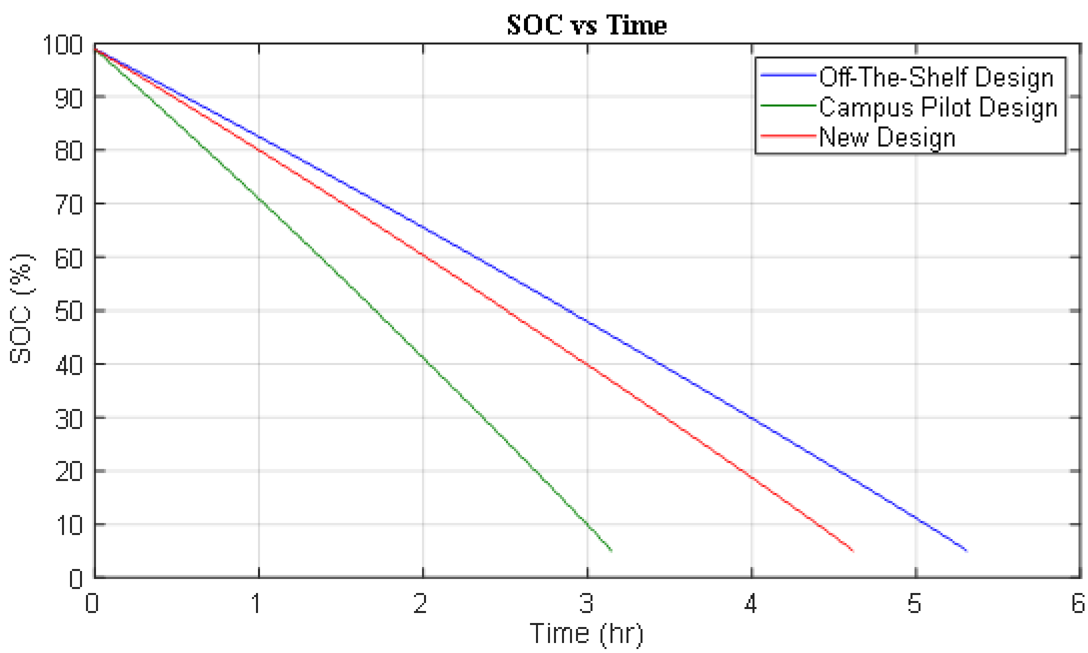


Figure 51. SOC vs time of three shuttle designs

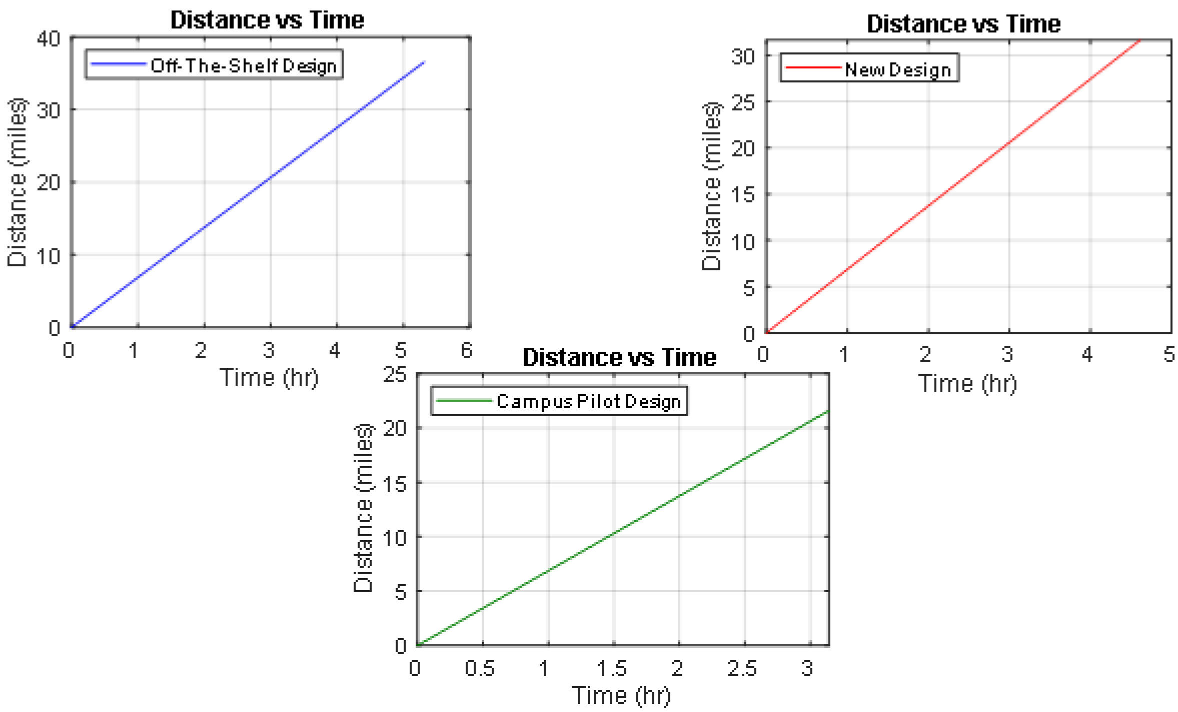


Figure 52. Operating range of the three autonomous shuttles

4.4 Cost analysis

The costs associated with our model were divided into fixed and variable costs. The fixed costs associated with our model were purchase price, operator salary, and interest of the shuttle price. For our variable costs, we considered depreciation of the vehicle, and operator salary raises maintenance costs and electricity costs. The total cost was determined and plotted to observe the implications of taking accessibility as an afterthought. The cost per passenger was also determined because this is an important parameter in ridesharing. The cost per passenger was determined by dividing the total cost by the total number of passengers per year. These total cost and cost per passenger were plotted using MATLAB and are shown in Figure 53 and 54.

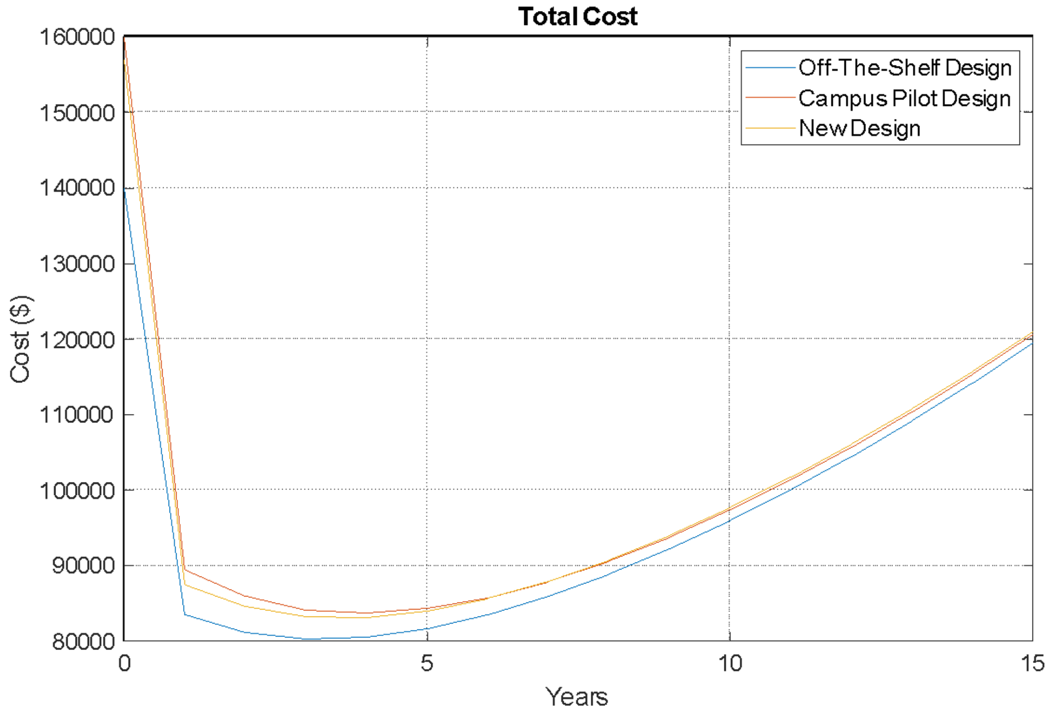


Figure 53. Total costs of the three shuttle designs

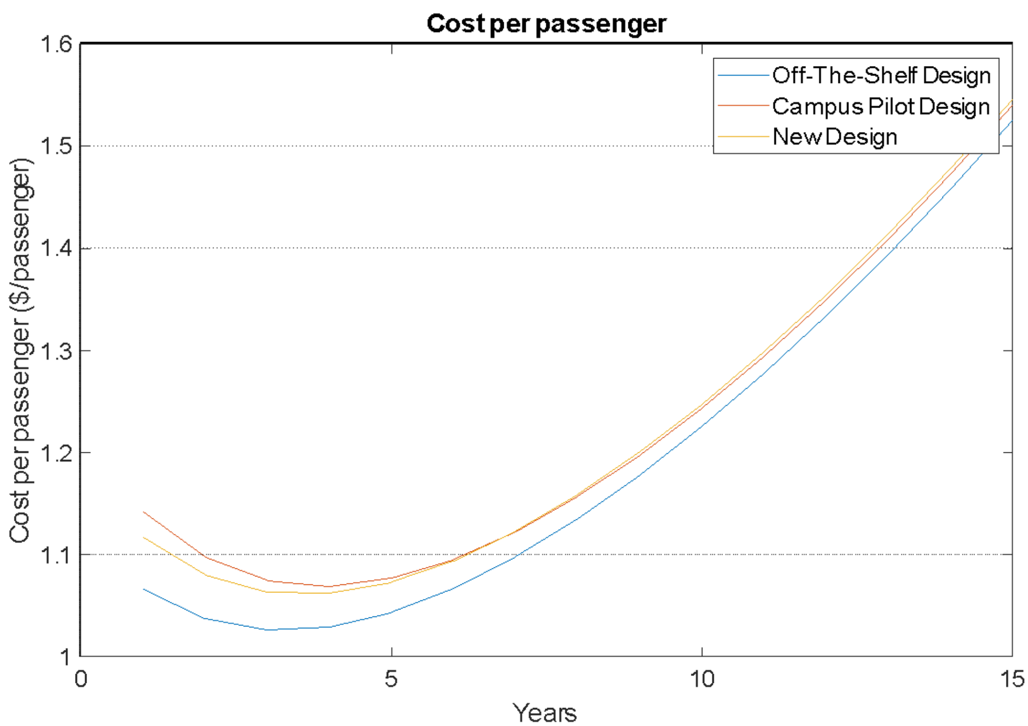


Figure 54. Cost per passenger of the three shuttle designs

The average cost per passenger of the three shuttles was obtained in order to better observe the tendency of these implications. The average cost per passenger was calculated and plotted using Microsoft Excel (see Figure 55).

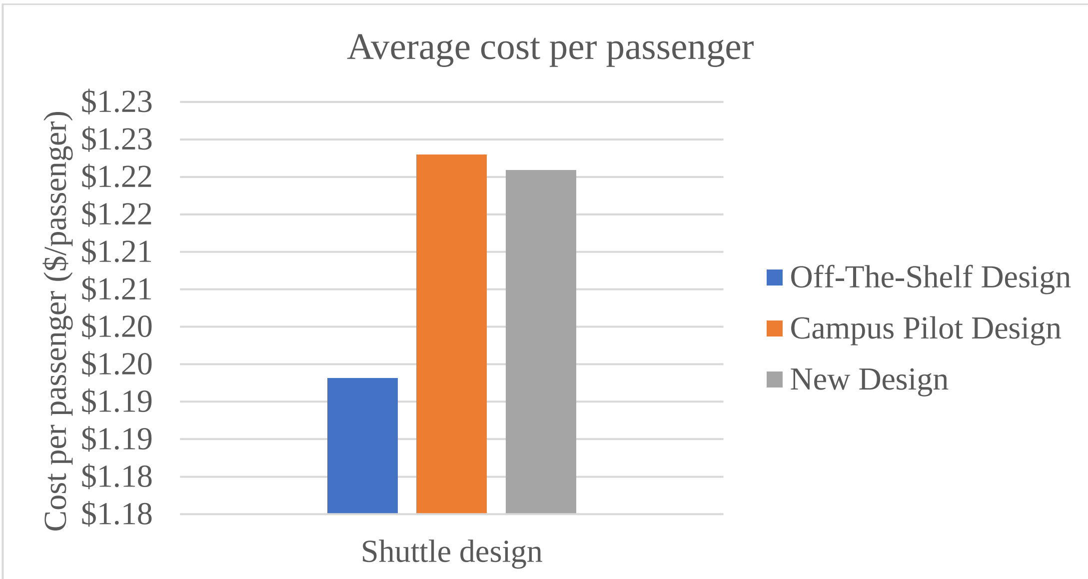


Figure 55. Average cost per passenger of the three shuttle designs

5 Discussion

This study describes the consequences and compromises to vehicle performance from post-production modifications in an attempt to encourage considerations for accessibility early in the design process. The effects of modifying an automated electric shuttle for wheelchair access on vehicle performance were assessed using computer-based simulation tools. Findings from the current study show that modifications to the vehicle for accessibility, have a positive and negative impact on vehicle dynamics. Despite the increase in stability gained due to the extended wheelbase, a decrease in maneuverability and battery energy capacity was obtained. These negative impacts due to post-production modifications could have been avoided if accessibility was considered in the early design process. Our new design (with increased wheelbase and track), is the perception of the specifications we think an autonomous shuttle should have for wheelchair accessibility. In Figures 26-32, we see that our new design overcomes in vehicle performance the previous designs.

Simulation results also suggest passenger experience may be compromised in the process of post-production modification. The vertical acceleration of the vehicle is directly related to the ride comfort of the passenger since the human body can only be exposed to a certain amount of vibrations [52][53]. In the version of the shuttle relying on post-production modifications (campus pilot design), there was a decrease in vertical displacement, pitch, and roll angle due to the increasing instability of the vehicle. However, there was a small increase in the vertical acceleration of the chassis due to the suspension parameters. This finding indicates that in modifying post-production for accessible accommodations, designers and engineers are not able to fully account for user experience as they might in the main design phase. This may have been due to time constraints in attempting to decrease the ADA-compliant shuttle's time to market. In comparison, in creating a new design of the shuttle, the accessibility specifications were known at the beginning; therefore, vehicle requirements such as suspension parameters, steering geometry, suspension geometry, battery type, and configuration could be selected to complement the accessibility-related specifications.

From our active suspension analysis of the new design, we obtained the outstanding benefits of applying this system to a vehicle in order to improve ride quality. This system provides more vehicle stability and fewer vibrations exerted to the passengers due to the variable damping force that minimizes the vehicle's vertical acceleration. Also, by performing a co-simulation, we validated that active suspension systems have a greater impact on ride quality than passive suspension systems on actual vehicles. This suspension system is not integrated into all vehicles because it’s very costly. Nevertheless, from Figure 53 and 54, we can see that even if we apply this expensive system to the new design, the cost implications between the new design and the campus pilot design are minimum.

Simulation results indicated that the campus pilot design decreased performance in terms of a nearly 39% decrease in operating range and 42% in operating time, and less maneuverability due to a 28% increase in turning radius. The new design, on the other hand, demonstrated improved performance over the campus pilot design in terms of range and time to discharge but did not quite reach the range of the off-the-shelf design. One reason the off-the-shelf design outperformed the new version may be due to the compromises it made with accessibility.

The performed cost analysis gave us some insight into the implications in terms of costs that post-production modifications can have on autonomous vehicle designs. This analysis was performed with estimations and approximations we thought the purchase prices and the modifications would cost. We observed the new design possesses less total costs and less cost per passenger than the campus pilot design (shuttle with post-production modifications), which validates our hypothesis of post-production modifications being more costly than considering design in the early design process. Even though the average cost per passenger was significantly small between the campus pilot design and the new design ($0.01), we still obtained less cost for the new design. This small difference is due to the assumptions made for the purchase prices and the post-production modification costs for our analysis. In a real-world application, you would observe substantial differences.

6 Conclusion

There is a clear benefit to early consideration of accessibility accommodations within vehicle shuttle design, both in terms of percent population accommodated and simulated vehicle performance. In contrast, post-production consideration and modification to add on accessibility accommodations and adjust affected vehicle parameters around the change results in compromises to intended performance.

Simulated vehicle performance and digital engineering design tools provide a powerful means of the cost-effective analysis of vehicle design prior to production. In this way, designers may explore various parameters to optimize between desired accessibility and performance targets. Future work in this area includes applying accessibility considerations to provisions such as stop request buttons, emergency features, and user experience with communication to the autonomous shuttle. Due to the absence of a driver and the potential absence of an operator or assistance, it is crucial that research investigating autonomous shuttles understand that this paradigm shift removes a potential resource to people with disabilities. Therefore, research investigating how independence can be ensured to this population throughout the full travel chain through effective and inclusive design is key. Future work also includes analysis of the cost and time impact of delayed implementation of accessibility to manufacturers and time to deployment.

Some aspects of the shuttle design were not changed between all three versions of the shuttle design. As part of a larger ongoing study, a usability evaluation was conducted on the campus pilot design and comments regarding vehicle step height, and ramp slope revealed they were acceptable and usable by people in manual and powered wheelchairs and people who use walking aids. For this reason, these values were not adjusted. This suggests that some aspects of the ADA as applied to public transit may be translated into autonomous shuttles, however since it has also been shown that there is a need to update ADA standards to accommodate the changing population and evolving technology of assistive aids, studies directly investigating the barriers to use and needs of people with disabilities and older adults within driverless shuttles is needed[54]. A parallel study currently aims to optimize the suspension tuning for the new design based on the known tuning parameters from both the off-the-shelf and the campus pilot design. This study will result in corresponding values for roll, pitch, acceleration for the new design. These key parameters are directly affected by the suspension tuning specification and are also indicators of passenger comfort and safety [55].

One limitation of this present study is that the new design was generated with certain parameters such as wheelbase and wheel track controlled in order to scope the design of the shuttle. As a result, the design space was inherently limited, and the new design does not represent a fully designed or optimized vehicle and reflects a bias towards design decisions made in the off-the-shelf shuttle. However, since the simulation parameters were selected by retaining features of the currently deployed campus pilot shuttle, we believe the simulation of the new design is representative of a simplified shuttle that does, in fact, illustrate early design consideration for accessibility. In future work, a stochastic optimization problem may be framed such that the design space may be fully explored. Another limitation of this study is that it does not investigate the time or financial cost incurred from the post-production modification process. In order to understand the full scope of the impact on manufacturers and time-to-market, these must be studied and quantified. This research may also be informative to industry and other stakeholders in understanding the importance of inclusive thinking during the initial design ideation.

7 References

[1]. Maureen A. Linden, Derek G. Kamper, Steven I. Reger, Thomas C. Adams. 1996. "Transportation Needs: Survey of Individuals with Disabilities."

[2]. Ferrari, Laura, Michele Berlingerio, Francesco Calabrese, and Jon Reades. 2014. "Improving the Accessibility of Urban Transportation Networks for People with Disabilities." *Transportation Research Part C: Emerging Technologies* 45 (August): 27–40.

[3]. Casas, Irene. 2007. "Social Exclusion and the Disabled: An Accessibility Approach." *The Professional Geographer: The Journal of the Association of American Geographers* 59 (4): 463–77.

[4]. Bascom, Graydon. 2017. "Transportation Related Challenges for Persons' with Disabilities Social Participation." Utah State University. https://digitalcommons.usu.edu/etd/5265/.

[5]. Brault, M.W., Americans with disabilities: 2010, Current Population Reports. 2012, U.S. Census Bureau: U.S. Census Bureau, Washington, DC. p. P70-131.

[6]. Flagg, J., Wheeled Mobility Demographics, in Industry Profile on Wheeled Mobility, S. Bauer and M.E. Bunning, Editors. 2009, RERC on Technology Transfer: Buffalo, NY.

[7]. LaPlante, M.P. and H.S. Kaye (2010). Demographics and Trends in Wheeled Mobility Equipment Use and Accessibility in the Community. Assistive Technology: The Official Journal of RESNA, 2010. 22(1): p. 3 – 17.

[8]. Bezyak, Jill L., Scott A. Sabella, and Robert H. Gattis. 2017. "Public Transportation: An Investigation of Barriers for People With Disabilities." Journal of Disability Policy Studies 28 (1): 52–60.

[9]. Field, Marilyn J., Alan M. Jette, and Institute of Medicine (US) Committee on Disability in America. 2007. *Transportation Patterns and Problems of People with Disabilities*. National Academies Press (US).

[10]. Bascom, Graydon W. 2017. "TRANSPORTATION RELATED CHALLENGES FOR PERSONS WITH DISABILITIES." Edited by Keith M. Christensen. UTAH STATE UNIVERSITY. https://laep.usu.edu/files/thesis-bascorn.pdf.

[11]. US Access Board. (2008). Draft revisions to the ADA accessibility Guidelines for buses and vans. Federal Register (36 CFR Part 1192). Retrieved from United States Access Board website: https://www.access-board.gov/vguidedraft2.htm.

[12]. Wood, S.P. et al., 2012. The Potential Regulatory Challenges of Increasingly Autonomous Motor Vehicles Symposium Article. Santa Clara law review, (4), pp.1423–1502.

[13]. Balog, J.N. et al., 1992. Accessibility handbook for transit facilities, United States. Joint Program Office for Intelligent Transportation Systems. Available at: https://rosap.ntl.bts.gov/view/dot/2624.

[14]. Cross, D., Wheelchair access: Improvements, Standards and Challenges. Available at: http://www.douglasjcross.com/d_Cross_2006_APTA_paper.pdf.

[15]. Claypool, Henry, Amitai Bin-Nun, and Jeffrey Gerlach. 2017. "Self -Driving Car: The Impact on People with Disabilities."

[16]. Sashank Allu, Ayush Jaiswal, Michael Lin, Anjali Malik, Levin Ozay, Tarun Prashanth, Dr. Bradley S. Duerstock. n.d. "Accessible Personal Transportation for People with Disabilities Using Autonomous Vehicles." https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1000&context=ugcw.

[17]. Gillespie, Thomas D. 1992. "Fundamentals of Vehicle Dynamics." *Society of Automotive Engineers*.

[18]. Yang, Shaopu, Yongjie Lu, and Shaohua Li. 2013. "An Overview on Vehicle Dynamics." *International Journal of Dynamics and Control* 1 (4): 385–95.

[19]. Harper, Corey D., Chris T. Hendrickson, Sonia Mangones, and Constantine Samaras. 2016. "Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions." Transportation Research Part C: Emerging Technologies 72 (November): 1–9.

[20]. Bradshaw-Martin, H. & Easton, C., 2014. Autonomous or "driverless" cars and disability: a legal and ethical analysis. European Journal of Current Legal Issues, 20(3). Available at: http://webjcli.org/article/view/344 [Accessed July 30, 2019].

[21]. Wiseman, Y., 2019. Autonomous Vehicles. Available at: https://heinonline.org/HOL/Page?handle=hein.journals/jltp2013&div=15&g_sent=1&casa_token=&collection=journals.

[22]. Bharathy, A., and D'Souza, C. (2018). Revisiting clear floor area requirements for wheeled mobility devices in public transportation. Transportation Research Record, Vol. 2672(8), 675-685. DOI: 10.1177/0361198118787082.

[23]. D'Souza, C., Steinfeld, E., Paquet, V., & Feathers, D. (2010). Space requirements for wheeled mobility devices in public transportation: An analysis of clear floor space requirements. Transportation Research Record: Journal of the Transportation Research Board, No. 2145(1), 66-71. DOI: 10.3141/2145-08

[24]. Steinfeld, E., Paquet, V., D'Souza, C., Joseph, C., & Maisel, J. (2010a). Anthropometry of Wheeled Mobility Project: Final report to the U.S. Access Board. IDeA Center, Buffalo, NY, December 2010.

[25]. Steinfeld, E., Maisel, J., Feathers, D., & D'Souza, C. (2010b). Anthropometry and standards for wheeled mobility: an international comparison. Assistive Technology, Vol. 22(1), 51-67. DOI: 10.1080/10400430903520280

[26]. Matsuoka, Yoshiyuki, Kohei Kawai, and Ryo Sato. 2003. "Vibration Simulation Model of Passenger-Wheelchair System in Wheelchair-Accessible Vehicle." *Journal of Mechanical Design* 125 (4): 779–85.

[27]. Vingbäck, Johan, Peter Jeppsson, and Jan van Deventer. 2015. "Evaluating Ride Comfort for Wheelchair Passengers Utilizing a Motionbase Simulator." In *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection.

[28]. Aziz Sezgin, Yunus Ziya Arslan. n.d. "Analysis of the Vertical Vibration Effects on Ride Comfort of Vehicle Driver." Accessed February 8, 2020. https://www.researchgate.net/profile/Aziz_Sezgin/publication/230854924_Analysis_of_the_vertical_vibration_effects_on_ride_comfort_of_vehicle_driver/links/0912f50dc4bb17db16000000/Analysis-of-the-vertical-vibration-effects-on-ride-comfort-of-vehicle-driver.pdf

[29]. Polack, P., F. Altché, B. d'Andréa-Novel, and A. de La Fortelle. 2017. "The Kinematic Bicycle Model: A Consistent Model for Planning Feasible Trajectories for Autonomous Vehicles?" In *2017 IEEE Intelligent Vehicles Symposium (IV)*, 812–18.

[30]. Ashwin Carvalho, Yiqui Gaho, Stephanie Lefevre, Francesco Borelli. n.d. "Stochastic Predictive Control of Autonomous Vehicles in Uncertain Environments." Accessed February 7, 2020. https://www.researchgate.net/profile/Stephanie_Lefevre3/publication/263308694_Stochastic_predictive_control_of_autonomous_vehicles_in_uncertain_environments/links/0f31753a85c205a92c000000.pdf.

[31]. Falcone, P., F. Borrelli, J. Asgari, H. E. Tseng, and D. Hrovat. 2007. "Predictive Active Steering Control for Autonomous Vehicle Systems." *IEEE Transactions on Control Systems Technology* 15 (3): 566–80.

[32]. Choi, J., R. Curry, and G. Elkaim. 2008. "Path Planning Based on Bézier Curve for Autonomous Ground Vehicles." In *Advances in Electrical and Electronics Engineering - IAENG Special Edition of the World Congress on Engineering and Computer Science 2008*, 158–66.

[33]. Elbanhawi, M., M. Simic, and R. Jazar. 2015. "In the Passenger Seat: Investigating Ride Comfort Measures in Autonomous Cars." *IEEE Intelligent Transportation Systems Magazine* 7 (3): 4–17.

[34]. Hayafune, Kazuya, and Hiroaki Yoshida. 1990. "Control Method of Autonomous Vehicle Considering Compatibility of Riding Comfort and Vehicle Controllability." SAE Technical Paper. https://doi.org/10.4271/901486.

[35]. Marzbani, H., H. Khayyam, C. N. To, Đ. V. Quoc, and R. N. Jazar. 2019. "Autonomous Vehicles: Autodriver Algorithm and Vehicle Dynamics." *IEEE Transactions on Vehicular Technology* 68 (4): 3201–11.

[36]. Scott-Webber, Lennie, and Anna Marshall-Baker. 1998. "Two Contrasting Approaches to Urban Accessibility for Individuals with Disabilities or Special Needs." *Journal of Urban Technology* 5 (1): 1–15.

[37]. Jaeger, Paul T., and Bo Xie. 2009. "Developing Online Community Accessibility Guidelines for Persons With Disabilities and Older Adults." *Journal of Disability Policy Studies* 20 (1): 55–63.

[38]. Roberts, Jodi B., Laura A. Crittenden, and Jason C. Crittenden. 2011. “Students with Disabilities and Online Learning: A Cross-Institutional Study of Perceived Satisfaction with Accessibility Compliance and Services.” *The Internet and Higher Education* 14 (4): 242–50.

[39]. Cardinal, Bradley J., and Marc D. Spaziani. 2003. “ADA Compliance and the Accessibility of Physical Activity Facilities in Western Oregon.” *American Journal of Health Promotion: AJHP* 17 (3): 197–201.

[40]. Rajamani, Rajesh. 2011. *Vehicle Dynamics and Control*. Springer Science & Business Media.

[41]. Guiggiani, Massimo. 2014. “The Science of Vehicle Dynamics.” *Pisa, Italy: Springer Netherlands*.

[42]. Butakov, V. A., and P. Ioannou. 2015. “Personalized Driver/Vehicle Lane Change Models for ADAS.” *IEEE Transactions on Vehicular Technology* 64 (10): 4422–31.

[43]. Vahidi, A., and A. Eskandarian. 2003. “Research Advances in Intelligent Collision Avoidance and Adaptive Cruise Control.” *IEEE Transactions on Intelligent Transportation Systems* 4 (3): 143–53.

[44]. Fagnant, Daniel J., and Kara Kockelman. 2014. “Preparing a Nation for Autonomous Vehicles: 1 Opportunities, Barriers and Policy Recommendations for 2 Capitalizing on Self-Driven Vehicles 3.” *Transportation Research* 20. https://www.caee.utexas.edu/prof/kockelman/public_html/TRB14EnoAVs.pdf.

[45]. “Automotive Suspension Systems.” n.d. https://www.cedengineering.com/userfiles/Automotive%20Suspension%20Systems.pdf.

[46]. Hassan, Samy A. 1986. “Fundamental Studies of Passive, Active and Semi-Active Automotive Suspension Systems.” University of Leeds. https://core.ac.uk/download/pdf/9257269.pdf.

[47]. Campos, J., Davis, L., Lewis, F. L., Ikenaga, S., Scully, S., & Evans, M., “Active suspension control of ground vehicle heave and pitch motions.” *Proceedings of the 7th IEEE Mediterranean Control Conference on Control and Automation* (pp. 222-233), June 1990.

[48]. Jazar, R. N., “Vehicle roll dynamics,” *Vehicle Dynamics: Theory and Application* (pp. 665-725), 2008.

[49]. Eric Tseng, H., Xu, L. & Hrovat, D., 2007. Estimation of land vehicle roll and pitch angles. Vehicle System Dynamics, 45(5), pp.433–443.

[50]. Watanabe, K., J. Yamakawa, M. Tanaka, and T. Sasaki. 2007. “Turning Characteristics of Multi-Axle Vehicles.” *Journal of Terramechanics* 44 (1): 81–87.

[51]. Hayes, J.G. et al., 2011. Simplified electric vehicle powertrain models and range estimation. In 2011 IEEE Vehicle Power and Propulsion Conference. pp. 1–5.

[52]. Oborne, D.J., 1983. Whole-body vibration and International Standard ISO 2631: a critique. *Human factors*, 25(1), pp.55–69.

[53]. Bouazara, M., Richard, M.J. & Rakheja, S., 2006. Safety and comfort analysis of a 3-D vehicle model with optimal non-linear active seat suspension. *Journal of Terramechanics*, 43(2), pp.97–118.

[54]. Tabattanon, K., Sandhu, N., D'Souza, C., “Accessible Design of Low-Speed Automated Shuttles: A Brief Review of Lessons Learned from Public Transit,” *Proceedings of the 63rd Annual Meeting of the Human Factors and Ergonomics Society (HFES)*, 2019.

[55]. Ikenaga, S., Lewis, F. L., Campos, J., & Davis, L. , “Active suspension control of ground vehicle based on a full-vehicle model,” *Proceedings of the 2000 American Control Conference. ACC (IEEE Cat. No.00CH36334)*. pp. 4019–4024 vol.6, 2000.