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Vehicle Performance Analysis of a Wheelchair Accessible Autonomous Electric Shuttle

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Abstract

Autonomous vehicles (AVs) 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. 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 (Automated Dynamic Analysis of Mechanical Systems), and Autonomie demonstrated that the modifications aimed at providing wheelchair access had important implications for vehicle dynamics (e.g., turning radius, pitch, roll), energy consumption (operating range and usage duration), and cost per passenger. A ride comfort analysis was performed using MATLAB to study the passenger's ride comfort in all three shuttle designs. Energy consumption and lateral dynamic analyses were performed to analyze the operating range and turning radius of the shuttles. Also a brief cost analysis provides insight into the cost implications of post-production modifications. Simulation results indicate aftermarket modifications have a large impact on the vehicle performance and increase the cost per passenger. The campus pilot shuttle design adversely affects the turning radius and reduces the 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.

Keywords

Mobility, Electric vehicles, Autonomous vehicles, Human factors

Introduction

Few shared autonomous vehicle (AV) designs consider accessibility for persons with mobility impairments prior to the first deployment. As a result, populations including the 21 million adults with mobility impairment and the 50 million older adults in the United States are potentially excluded from access to travel options that would otherwise greatly improve their mobility independence and safety [1, 2, 3, 4]. Although there are no current federal standards specific to shared autonomous shuttles, certain provisions in the Americans with Disabilities Act (ADA) standards for transit vehicles like vans and buses help inform the accessible design of early shared AV deployments [5, 6]. Shared AVs deployed without accessibility consideration must thus be modified post-production to include features such as access ramps and compliant clear floor space, resulting in increased cost, increased time within design iterations and time to deployment, and potentially compromised vehicle performance. There is a research gap related to quantifying the cost, time, and performance effects of post-production modifications for accessibility and the implications on the effectiveness of the overall design process. Information to aid the AV industry in addressing accessibility within the constraints of vehicle design early in the design process is also lacking [7]. To address this, simulations using computer-aided engineering tools and digital human modeling provide a cost-efficient and time-efficient means of exploring the effects of ranging design parameters on vehicle performance, usability, and accessibility [8]. Physics-based simulation tools allow designers to evaluate different driving situations and the safety implications for users [9].

Project Description

This paper uses the case study of a project carried out in 2019, which was aimed toward introducing an innovative shared AV transportation system to the Western Michigan University (WMU) campus. In this deployment, two low-speed electric automated shuttles, modified post-production, operate on a fixed route within the campus. The case study is used to describe experiences related to incorporating accessibility considerations for wheeled mobility device users and to showcase the availability of wheelchair-accessible automated electric shuttles. 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. This paper describes the process of generating target design specifications and the modifications made to achieve the current design of the deployed shuttle. In addition, this paper also analyzes an ideal scenario where a similar autonomous shuttle is designed with accessibility considerations from the onset.

The objective of this work is to demonstrate the need for early considerations for accessibility in design by comparing the performance of three designs of a shared autonomous shuttle using digital simulation tools, namely, (1) the off-the-shelf shuttle that was not wheelchair accessible, (2) the campus pilot shuttle modified to be wheelchair accessible, and (3) a new design with accessibility foresight. Results summarize the physical accessibility criteria used in the campus pilot and new design, and the vehicle performance criteria used in the comparative analysis. Benefits and trade-offs of these designs and modifications are discussed.

Methods

Target Vehicle Design Objectives

The baseline shuttle was evaluated prior to post-production modifications by domain area experts, including users of a manual wheelchair and a powered wheelchair. Vehicle modifications targeted accommodations for users of wheeled mobility devices (manual and powered wheelchairs), with an emphasis on achieving compliance with ADA accessibility standards [5, 6]. At this stage of the project, no modifications were made addressing other types of sensory and communicative disabilities. A description of the off-the-shelf shuttle and target designs for the campus pilot shuttle follows.

Off-the-shelf design: The off-the-shelf design prior to any adjustments for accessibility was a PodZero (Aurrigo, RDM Group, UK) low-speed electric automated (SAE Level 3) shuttle. This shuttle accommodates four seated passengers and operates at speeds up to 6.7 m/s. A major limitation of the shuttle was its inability to accommodate a wheeled mobility device primarily due to the absence of (1) adequate clear floor space, (2) a securement device, and (3) an access ramp for stepless ingress/egress.

Campus pilot design: To provide access for a passenger using a wheelchair, modifications to the vehicle chassis and passenger compartment with the following target design objectives were undertaken prior to deployment:

1. Increase the clear floor space and interior circulation space for the accommodation of a manual wheelchair.
2. Provide an access ramp for wheelchair entry and exit.
3. Provide adequate securement for the passenger while they are seated in their wheelchair.

Due to constraints on the available clear floor space of the off-the-shelf design and comparisons with wheelchair anthropometry data on occupied length and width and weight capacity, the campus pilot design was limited to accommodating only manual wheelchairs. This limitation was addressed within the concept for a new design where the target accommodation was both manual and powered wheelchairs.

New design: A 95th percentile target for manual and powered wheelchair accommodation was used. A web-based design tool [10] based on anthropometry measurements of 500 wheeled mobility device users in the United States was used to determine the dimensions for the following design features:

1. Door width: based on the 95th percentile dimension for occupied wheelchair width
2. Ramp width: based on the 95th percentile dimension for occupied wheelchair width
3. Ramp weight capacity: based on 95th percentile occupied wheelchair weight
4. Clear floor space during travel: based on the 95th percentile clear floor space length and width (Figure 1) [11]
5. Clear floor space during ingress-egress with a 90-degree turn: based on the 95th percentile clear floor space length and width

The analysis for wheelchair accommodation was limited to manual and powered wheelchairs and did not consider electric scooters. Certain characteristics of the off-the-shelf shuttle were retained, such as maximum occupancy of four ambulatory passengers (or 2 ambulatory and 1 wheelchair user from the campus pilot design), curb-side entry, and a forward-facing wheelchair securement position. Gross Vehicle

FIGURE 1 Anthropometry-based design tool used to determine the spatial dimensions needed to accommodate 95% of manual and powered wheelchairs. “Image Source: Inclusive Mobility Research Lab, University of Michigan, Ann Arbor.”

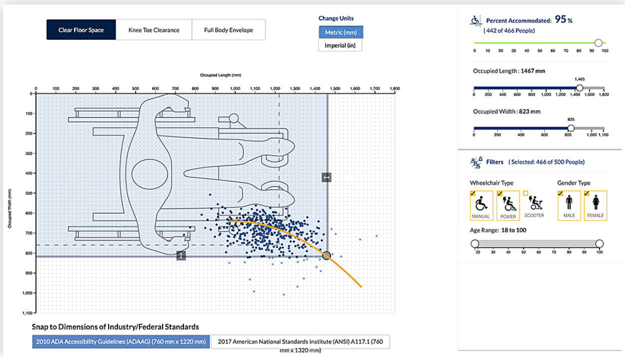

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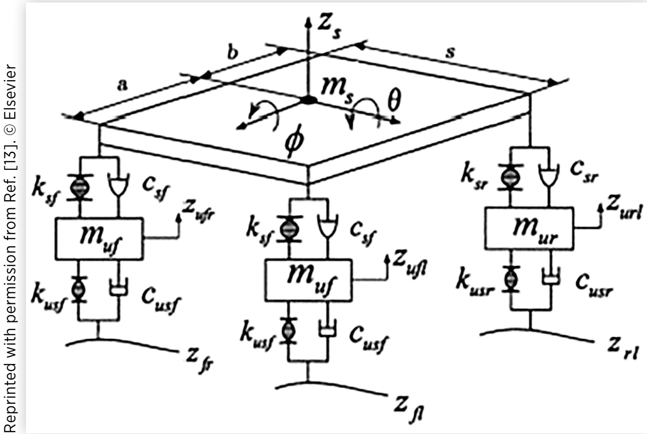
FIGURE 2 Mechanical model of a vehicle suspension system [13].



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Mass (GVM) was determined as the heavier of the two passenger conditions calculated using the mass of a 95th percentile adult male using NHANES 2011-2014 anthropometry data [12] and the occupied mass of powered wheeled mobility devices [10].

Ride Comfort Analysis

A ride comfort analysis was performed in MATLAB 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. Parameters considered in the 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.

Mathematical Modeling

A mathematical model of the vertical dynamics of a vehicle was derived from analyzing the vehicle response to various road inputs. Our system possesses 7 degrees of freedom, and it is commonly used to study the ride dynamics of a vehicle. The level of vibration exerted to passengers is an important criterion to evaluate ride comfort in a vehicle design, 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 2 represents our full vehicle model and the sign convention used to derive the equations of motion.

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.

$$\ddot{z}_b = \frac{1}{m_b}\left(-F_{fr} - F_{rr} - F_{fl} - F_{rl}\right) \qquad \text{Eq. (1)}$$

$$\ddot{\Theta} = \frac{1}{I_{yy}}\left(l_f F_{fr} + l_f F_{fl} - l_r F_{rr} - l_r F_{rl}\right) \qquad \text{Eq. (2)}$$

$$\ddot{\phi} = \frac{1}{I_{xx}}\left(-b_l F_{fr} + b_r F_{fl} - b_l F_{rr} + b_r F_{rl}\right) \qquad \text{Eq. (3)}$$

where z_b is the chassis vertical displacement, Θ is the pitch, and ϕ is the roll. The inertial properties of the vehicle are represented as I_{xx}, I_{yy}, and m_b, where I_{yy} is the moment of inertia on the y axis, I_{xx} is the moment of inertia on the x axis, and m_b is the vehicle mass. l_f is the front axle-center of gravity (CG) distance, l_r is the rear axle-CG distance, b_f is the left tires-CG distance, and b_r is the rear tires-CG distance, while F_{fl}, F_{fr}, F_{rl}, and F_{rr} are the tire forces.

Parameters and Generated Inputs

To analyze the behavior of the vehicle, our analysis considered three different types of inputs to the system: (1) A step input was used representing a vertical displacement on the tires maintained at 0.05 m; (2) A rectangular pulse with a vertical displacement of 0.05 m for a duration of 0.5 sec followed by a return to baseline (0 m). In both previous cases, the roll angle was very small, and we could not 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. (3) A sine input to visualize the response of the vehicle roll angle. The sine input was delayed by 90 degrees between the right and left tire 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 2.2 m/s because, in the project, the vehicle was restricted to the walking speed of pedestrians for safety reasons. The parameters assumed for our simulation are shown in Table 1.

The simulation parameters of the off-the-shelf and campus pilot designs were taken from the shuttle provider and the company that performed the modifications.

TABLE 1 Parameters for modeling and simulation software.

Parameter	Off-the-self 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

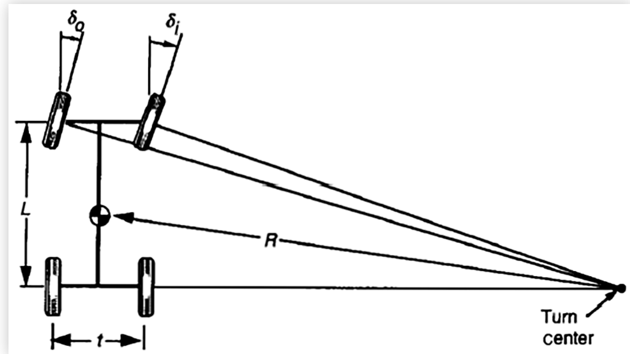
The moment of inertia was determined from the Computer-Aided Design (CAD) model of each shuttle design. The new design parameters were determined given the wheelbase and track necessary to meet the requirements of the ADA standards presented in the target vehicle design objectives section. We compared the dimensions of the new design with the work of [14]. Our shuttle was designed to carry one person in a wheelchair so the dimensions of the new design seem reasonable.

Turning Radius

A dynamic analysis of the three vehicle designs was conducted using the multibody dynamics simulation software, ADAMS (i.e., Automated Dynamic Analysis of Mechanical Systems; MSC Software Corporation, CA). For the analysis, vehicle models were created in ADAMS matching the dimensions of the three vehicle versions and with an Ackermann steering geometry to capture the response of the vehicles during handling situations. The vehicle dynamics analysis focused on the turning radius. This parameter is defined as the minimum radius required by a vehicle in a U-turn and measured from the center of the turning circle to the outer wheel of the vehicle. While many different equations for calculating turning radius are available [15], in its simplest form turning radius "R" depends on the wheelbase (distance "L" between the front and rear wheels), track (distance "t" between the two wheels of the same axle), and the measured angle "δ" of the outer wheel while performing the U-turn (Figure 3).

The calculations for turning radius assumed that the vehicle would turn at a low speed, i.e., a maximum operating speed of 2.2 m/s, with minimal slip angle, and the turning center lies in the projection of the rear axle. The turning radius for the off-the-shelf design obtained from the manufacturer's specifications was used to determine the maximum steering angle of the outer wheel using Equations 4 and 5. With these steering angles, we could determine the turning radius of the campus pilot design and the new design with the increased wheelbase is increased.

FIGURE 3 Geometry of a turning vehicle [16].



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$$\delta_o = \arctan\left(\frac{L}{\left(R+\frac{t}{2}\right)}\right) = \frac{L}{\left(R+\frac{t}{2}\right)} \quad \text{Eq. (4)}$$

$$\delta_i = \arctan\left(\frac{L}{\left(R-\frac{t}{2}\right)}\right) = \frac{L}{\left(R-\frac{t}{2}\right)} \quad \text{Eq. (5)}$$

where δ_o and δ_i are the outer and inner steering angles of the front tires, respectively; L is the wheelbase; t is track; and R is the radius of the curvature.

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 Laboratories to perform vehicle energy consumption and performance analysis. 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 drive cycles that can be used to perform energy consumption analysis of user-selected vehicle models and custom drive cycles.

Autonomie was used to determine the operating range of each shuttle design. The off-the-shelf design has a 6 × 8V lead-acid battery pack in series, and the campus pilot design has a 4 × 12V lithium iron phosphate battery pack in series. The selected battery configuration for the new design is a 6 × 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.

TABLE 2 Parameters used for Autonomie simulation software.

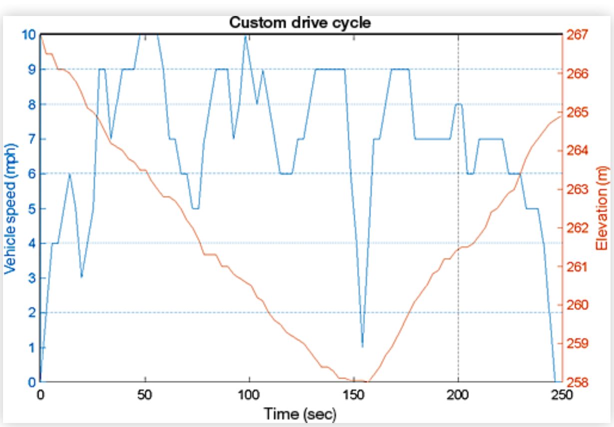
Parameter	Off-the-shelf design	Campus pilot design	New design
Rolling resistance	0.008	0.008	0.008
Drag coefficient	0.311	0.311	0.34
Capacity amps-hours (Ah)	176 (100 h)	110 (20 h)	167 (100 h)
Energy capacity per battery (kWh)	1.5	1.2	1.4
Voltage (V)	48	48	48
Horsepower (kW)	3.3	3.3	3.3
Min SOC (%)	5	5	5
Frontal area of the vehicle (m^2)	2.372	2.372	2.42
Rear axle ratio	14.76:1	14.76:1	14.73:1
Battery pack energy capacity (kWh)	8	4.8	8.4

Twelve-volt batteries were chosen because we wanted to use batteries with a similar energy capacity per battery to the campus pilot design.

The parameters of a preloaded electric vehicle model in Autonomie were matched to the specifications of our three autonomous shuttle designs and summarized in Table 2. For instatement of "less" creased fidelity/realism, this analysis used a custom drive cycle with a route matched to the intended service route on WMU's campus. The drive cycle was developed using an ELM327 connected to the CAN (Controller Area Network) bus through the On-Board Diagnostics (OBD II) port on a research vehicle driven on the service route at WMU's main campus. The downhill and uphill grade is approximately 3 degrees. The elevation of the driven route was collected by GPS sensors.

The velocity versus time data were recorded and appended in series to create a drive cycle sufficiently long enough to completely exhaust the vehicle battery. Figure 4 depicts the custom drive cycle.

FIGURE 4 Recording of the velocity versus time profile used in creating the 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** is defined as the total distance traveled per charge [17]. The range of an electric vehicle depends on 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 preloaded in the Autonomie modeling software.
- **Time to Discharge** is defined as the duration for which the battery will sustain a charge while operating at maximum speed. Example factors affecting discharge time include battery size, vehicle speed, surface incline, and motor power.

The parameters used for the energy consumption analysis of each design were taken from the specifications of the battery pack of each shuttle. Parameters such as drag coefficient and rolling resistance were assumed, taking into account that the drag coefficient increases in the final design due to the increase in the frontal area. The minimum State of Charge (SOC) was assumed as 5% to indicate that below this limit, the shuttle goes out of operation. The frontal area of each shuttle was determined using the CAD model of each design.

Cost Analysis

A brief cost model was developed to give a contrast to the implications of considering accessibility as an afterthought. With the estimated purchase prices, the electrical consumption of the shuttles outputted from Autonomie, a cost analysis was performed with the assumptions shown in Table 3.

Since a safety operator was used for WMU's campus pilot, we incorporated in our cost model an assumed salary of $55,000 per year and an annual raise of 5% per year. The shuttle worked on 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. The total cost and cost per passenger were compared for each design.

Results

Design Objectives

The following modifications were made to the off-the-shelf design in meeting the design target objectives, in respective order:

1. Translating the front and rear axles elongated the wheelbase and increased interior floor space. Further, flip-up seats (vs. fixed seats) increased the interior circulation space for ingress/egress and situating a wheelchair during travel while also ensuring seat

TABLE 3 Input for our cost model.

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	$95,000.00
Maintenance per mile ($/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

availability for the vehicle operator and one additional passenger/companion.

2. A retractable access ramp beneath the vehicle floor was added 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. A forward-facing, four-point wheelchair securement system and a lap/shoulder-belt occupant restraint system to ensure the safety of all passengers.

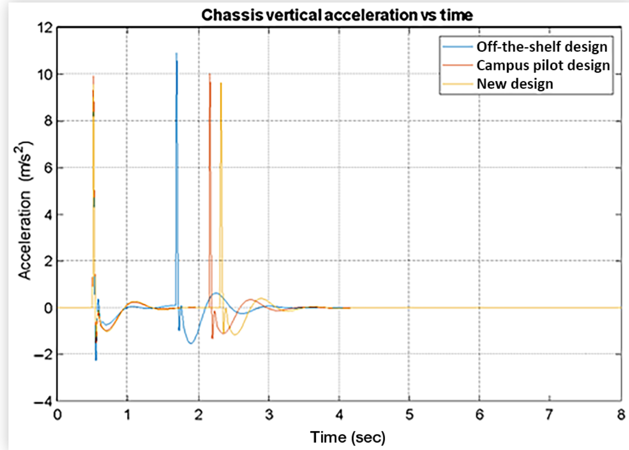
Increased interior dimensions for the new design were needed to accommodate the increased clear floor space length and width, as determined from the data-driven tool. The GVM of 522 kg representing 2 ambulatory passengers and one powered wheeled mobility device was used since it was higher than the mass of four ambulatory passengers (i.e., 500 kg).

Key output specifications of all three designs are summarized in Appendix A.

Ride Comfort Analysis

Simulation results indicate improvements in the ride quality due to the decrease in vertical displacement, pitch angle, roll angle, and vertical acceleration. The vertical acceleration of the off-the-shelf design, campus pilot design, and new shuttle design were 11 m/s^2, 10 m/s^2, and 9.8 m/s^2, respectively. The decrease in vertical acceleration indicates that the passenger will be exerted to lesser vibrations when the shuttle encounters road disturbances. As we can see in Figure 5, the new design has approximately 3% and 5% less vertical acceleration than the off-the-shelf and campus pilot design, respectively. This decrease was due to the suspension parameters chosen for the simulation, which indicates an improvement in ride quality.

FIGURE 5 Vertical acceleration of three shuttle designs submitted to step input.



The notable decrease between designs was in the vertical acceleration when the rear axle passes over the bump. Where the new design obtained a decrease of 11% with respect to the off-the-shelf design and 4% with respect to the campus pilot design.

The off-the-shelf design, campus pilot design, and new shuttle design exhibited a vertical displacement for the step input of 0.065 m, 0.06 m, and 0.061 m, respectively. When subjected to a rectangular pulse, the vertical displacement was reduced by approximately 0.025 m.

The highest amplitude of the roll angle of the off-the-shelf design, campus pilot design, and new design were 0.065 rad, 0.052 rad, and 0.045 rad, respectively (Figure 6). The pitch angle for a step input was approximately 0.01 rad in all designs as opposed to when subjected to a rectangular pulse as shown in Figure 7. This indicates a decrease in rolling motion when submitted to cornering scenarios. The decrease in pitch angle and roll angle indicates an increase in ride quality during bumps and cornering situations. The new design outperformed previous designs due to the increased wheelbase (which lowered the CG) and suspension parameters.

FIGURE 6 Roll angle of three shuttle designs submitted to sine input.

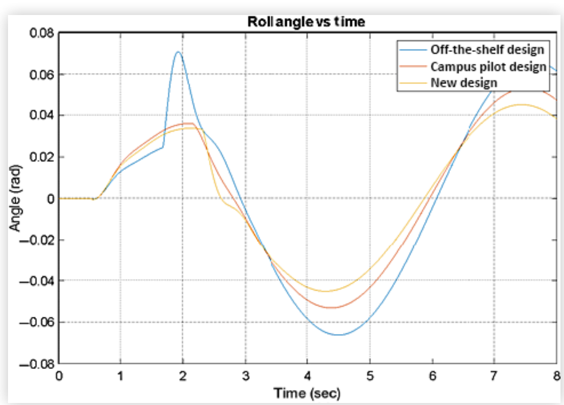
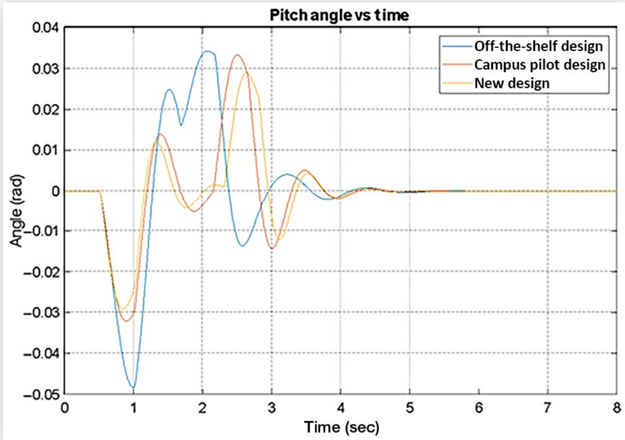


FIGURE 7 Pitch angle of three shuttle designs submitted to rectangular pulse.



In Figure 7, we see how the pitch oscillations are significantly reduced due to the suspension parameters and the increased time lag between the front and rear tires. This time lag increases as the wheelbase increases. Therefore, a bigger wheelbase means pitching oscillations and better ride quality when encountering road bumps.

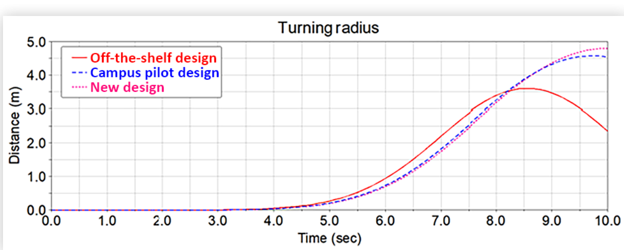
Turning Radius

Simulation results obtained from ADAMS indicate that the turning radius of the off-the-shelf, campus pilot, and new design were 3.5 m, 4.5 m, and 4.8 m, respectively. The increase in turning radius indicates an increase in stability, but a decrease in maneuverability. Hence, the increase in wheelbase due to the required modifications also carries a negative impact to the vehicle maneuvering. The turning radius of the three designs are shown in Figure 8.

Energy Consumption Analysis

Simulation results indicated that the time to complete discharge for the off-the-shelf design and new design were similar at 5.4 h and 4.6 h, respectively. The time to discharge for the modified shuttle design was substantially less at 3.2 h. Analysis results for the total distance traveled versus time were most promising for the off-the-shelf design at 37 miles in 5.25 h. Corresponding results for the campus pilot shuttle and new shuttle design were 22 miles in 3.15 h and 32 miles in 4.5 h, respectively. The new shuttle design traveled fewer miles than the off-the-shuttle design despite having more energy capacity due to the weight and electrical consumption of the shuttle as we can see in Appendix A.

FIGURE 8 Turning radius of the three autonomous shuttles.



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. The estimated fixed costs were $140,000, $160,000, and $150,000 for the off-the-shelf design, campus pilot shuttle design, and new shuttle design, respectively, in the first year. Variable costs included depreciation of the vehicle, operator salary raises, maintenance costs, and electricity costs. The variable cost amounted to $5000/year. Figure 9 plots the total cost per year for the three vehicle designs to convey the cost implications of taking accessibility as an afterthought. Results from our cost model indicate the campus pilot design has a higher total cost than other designs due to the post-production modifications made for wheelchair accessibility. The new design accounted for all these features in the design process and had a lower cost in a period of 15 years.

The cost per passenger is an important parameter in ridesharing and was computed as the total cost divided by the total number of passengers per year. Figure 10 plots the cost per passenger per year for the three vehicle designs. The campus pilot design presented a higher cost per passenger in comparison to previous designs due to post-production modifications in a period of 15 years. The average cost per passenger over a 15-year period for the off-the-shelf design, modified shuttle pilot, and new design were $1.19, $1.22, and $1.21, respectively.

Discussion

This study provides quantitative analyses on the consequences and compromises to vehicle performance from post-production modifications for accessibility versus accessibility considerations made early in the design process. The overarching purpose was to emphasize the improved performance and lower costs by

FIGURE 9 Total costs of the three shuttle designs.

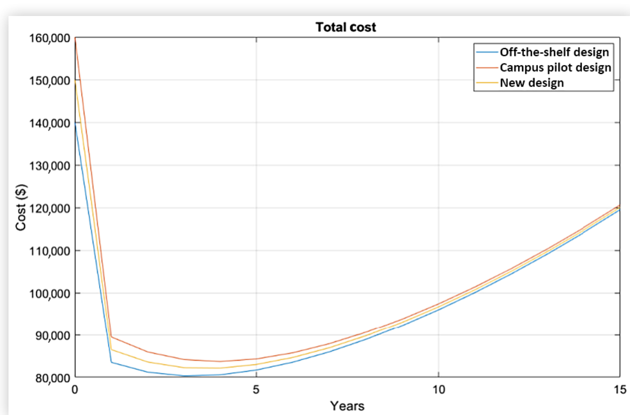
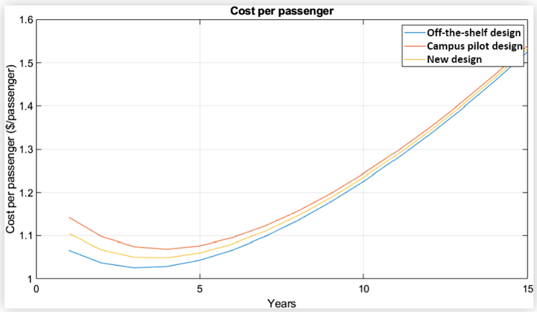


FIGURE 10 Cost per passenger of the three shuttle designs.



incorporating accessibility in emerging shared AVs at the early conceptual stages of design. 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 had some positive and negative impacts on vehicle dynamics. The increase in stability gained due to the extended wheelbase had a concomitant decrease in maneuverability and battery energy capacity. 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) incorporated minimum benchmark specifications we think an autonomous shuttle should have for wheelchair accessibility. Findings on improved ride quality, energy consumption, and cost implications indicate that our new wheelchair-accessible design overcomes the deficiencies in vehicle performance encountered in the campus pilot design.

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 certain amounts of vibrations [18, 19]. 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. Although there was a slight decrease in vertical displacement, roll, and pitch angle compared to previous designs, the purpose of this paper is to demonstrate the trade-offs due to afterthought modifications that could have been avoided by considering accessibility in the early design stage. The results may be more significant with a vehicle with a different wheelbase or track. 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 initial design phases for the off-the-shelf design. This may have been due to time constraints in attempting to decrease the time to market of the ADA-compliant shuttle. 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.

Simulation results indicated that the campus pilot design decreased performance in terms of a nearly 39% 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.

Findings from the cost analysis provide insight into the cost implications that post-production modifications can have on AV designs. This analysis was performed with cost estimates and approximations based on input from the vehicle manufacturer, operator representatives, and engineers that performed the vehicle modifications to the off-the-shelf design prior to pilot deployment. Results suggest that the total costs and less cost per passenger the new design possesses would be less than the campus pilot design (shuttle with post-production modifications), supporting our hypothesis that post-production modifications would be more costly than considering accessible 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. Based on economies of scale, these small cost differences could materialize into more substantial cost savings in a real-world application.

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 result in compromises to intended performance.

Simulated vehicle performance and digital engineering design tools provide a powerful and cost-effective means for analyzing vehicle designs prior to production and/or deployment. In this way, designers may explore various parameters to optimize between the 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 for 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 an 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 accessibility standards as applied to public transit may translate to shared autonomous shuttles. However prior research also suggests a need for updating the ADA accessibility standards to accommodate the changing population and evolving technology of assistive aids, and studies directly investigating the barriers to use and needs of people with disabilities and older adults within shared automated shuttles are needed [7]. 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, and 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 [20]. It is worth noting that even though we had a full vehicle model in ADAMS, it was only used for the turning radius analysis because the shuttle does not perform obstacle avoidance maneuvers. The shuttle simply stops and waits for the obstacle to get out of its path, or the safety operator takes control. Future work in this area includes expanding our analysis to obstacle avoidance for low-speed autonomous shuttles.

One limitation of the present study is that the new design was generated with certain parameters such as wheelbase and wheel track controlled to scope the design of the shuttle. As a result, the design space was inherently constrained, and the new design does not represent a fully designed or optimized vehicle and reflects a bias toward 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. 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.

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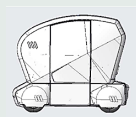
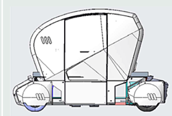
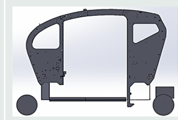
Appendix A

Key design specifications of each shuttle analyzed (* percent wheelchairs accommodated based on Design Guidelines for Wheeled Mobility Accessibility) [10].

	Off-the-shelf design	Campus pilot design	New design
Vehicle side view			
Accessibility specifications			
Seating capacity	4 ambulatory passengers	4 ambulatory passengers or 2 ambulatory and 1 passenger in a wheelchair	Same as modified design
Seating configurations	2-person forward-facing bench seat + 2-person rear-facing bench seat	2-person forward-facing flip-up bench 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
Floor height from ground (mm)	255	255	255
Access ramp dimensions (mm)	N/A	2140 length × 735 width	2140 length × 816 width
Maximum access ramp slope (when deployed to the ground)	N/A	1:8	1:8
Ramp weight capacity	N/A	204 kg (450 lb)	272 kg (600 lb)
Door width (mm) (% wheelchairs accommodated)	790 (92%)	790 (92%)	816 (95%)
Door height from the vehicle floor (at lowest point) (mm)	1450	1450	1450
Interior clear floor space during ingress/ egress (all seats folded up) (mm)	N/A	1275 length × 950 width	1950 × 950 (95%)
Clear floor space during travel (mm) (% wheelchairs accommodated)	N/A	1135 length × 762 width (36%)	1385 × 950 (95%)
Wheelchair securement	N/A	Forward-facing 4-point active tie-down	Forward-facing 4-point active tie-down
General vehicle specifications			
Wheelbase (mm)	1620	2280	2500
Track (mm)	1120	1120	1200
Seating capacity	4 passengers	4 passengers or 2 seated passengers and 1 passenger in a wheelchair	4 passengers or 2 seated passengers and 1 passenger in a wheelchair
Gross vehicle mass (GVM, kg)	1000	1065	1115
Battery type and configuration	6 × 8V lead-acid batteries in series	4 × 12V lithium iron phosphate batteries in series	6 × 12V lithium iron phosphate batteries in series
Energy capacity (kWh)	8.0	4.8	8.4

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