Agenda

Introduction
  • Introduction
  • Accessibility
  • Autonomous vehicles and accessibility
  • Vehicle dynamics and accessibility
  • Novel contributions
Methodology
  • Methodology
  • WMU project overview
  • Ride comfort study
  • Lateral dynamics
  • Energy consumption analysis
Results
  • Results
  • Passive suspension analysis
  • Active suspension analysis
  • ADAMS/MATLAB Co-simulation
  • Lateral dynamics
  • Energy consumption analysis
  • Cost analysis
Conclusion
  • Conclusion
  • Summary
  • Conclusion
  • Future Work
Acknowledgment

University Faculty
- Dr. Zachary Asher
- Dr. Mitchel Keil
- Dr. Kapseong Ro
- Dr. Clive D’Souza

Graduate Students
- Nick Goberville
- Nicholas Brown
- Amol Patil
- Yogesh Jagdale
- Farhang Motallebiaraghi
- Tushar Gaikward
- Parth Kadav
- Marsad Zoardar
- Kamolnat Tabattanon
What is the relationship between accessibility, autonomous vehicles and vehicle dynamics?
Venn diagram assessment

Accessibility

Autonomous vehicles

Vehicle dynamics
Autonomous vehicles

- A self-driving car, also known as an autonomous vehicle (AV), is a vehicle that is capable of sensing its environment and moving safely with little or no human input.

- The development and mass production of self-driving cars, has the potential to revolutionize transportation mobility and safety.

- Human error is involved in 94%-96% of car accidents.
Vehicle dynamics

Introduction

Vehicle dynamics is concerned with the movement of vehicles on a road surface. These movements are acceleration, braking, ride and handling.

Vehicle dynamics study the forces acting on the vehicle when the tires are submitted to a given input; for example:

- Steer input
- Vertical displacement
- Angular velocity

[Guiggiani, Massimo., The Science of Vehicle Dynamics (2014)]
Individuals with disabilities face barriers when it comes to public/private transportation due to the lack of good vehicle and facility design.

Users of wheeled mobility devices are particularly impacted by poor vehicle design.

The cost of retro-fitting a vehicle with special features is between $20,000-$80,000 on top of the purchase price of the vehicle.

Autonomous vehicles and accessibility

- 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.

- Design of AVs may require a higher standard of accessibility to ensure that passengers with disabilities can independently use these vehicles without driver assistance.

[Harper, Corey D., Chris T. Hendrickson, Sonia Mangones, and Constantine Samaras., Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions (2016)]
Autonomous vehicles and vehicle dynamics

Introduction

Research on autonomous vehicles has mainly focused on perception, planning, and control.

Control of the vehicle dynamics of an autonomous vehicle in the decision-making process is crucial because of uncertainties and safety risks.

Existing technologies:
- ADAS (Advanced driver-assistance systems)
- Lane keeping
- Stability control
- Path planning

References:
[Hayafune K., Hiroaki Y., Control Method of Autonomous Vehicle Considering Compatibility of Riding Comfort and Vehicle Controllability(1990)]
Accessibility and vehicle dynamics

- Accessible vehicles increase mobility for individuals with disabilities, but they tend to increase fatigue and discomfort on passengers due to poor vehicle design.

- Vehicle vibrations affects the passenger’s health and comfort

- Accessibility and vehicle dynamics is a poorly studied research area

Venn diagram assessment

Accessibility

Autonomous vehicles

Vehicle dynamics

- Well understood
- Not well understood
- Has not been studied
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.

The project was supported by the Michigan Department of Transportation to fund pilot transportation projects that solve mobility challenges for seniors, persons with disabilities and veterans throughout Michigan.
Engineering Inputs

Key design objectives

• Increase the available clear floor space by translating the front and rear axles thereby elongating the wheelbase

• Installing a retractable access ramp beneath the vehicle floor to allow for stepless ingress/egress.

• Installing flip-up seats (vs. fixed seats) to increase the interior circulation

• Provisions for a forward-facing, four-point wheelchair securement system and a lap/shoulder-belt occupant restraint system
Operation of the autonomous shuttles at Western Michigan University

• The shuttles operated on a fix 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

• A safety operator is always on board for safety purposes and to assist wheelchair users to ingress the shuttle
Survey Data

**Graph 1:**
- **Interacted with AV**
  - Yes: 202 (66%)
  - No: 94 (30%)
  - NA: 12 (4%)

**Graph 2:**
- **Level of safety risk an AV poses pedestrian**
- Scale of safety risk for pedestrian 1-5
- Number of participants:
  - Scale 1: 113
  - Scale 2: 92
  - Scale 3: 53
  - Scale 4: 20
  - Scale 5: 16
  - NA: 14

MS Eng. Johan Fanas Rojas
Survey Data

Expected impact a fleet of AV operating on pedestrian walkway will have on the accessibility of the walkway

<table>
<thead>
<tr>
<th>Expected level of impact</th>
<th>Number of participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>None at all</td>
<td>21</td>
</tr>
<tr>
<td>A little</td>
<td>80</td>
</tr>
<tr>
<td>A moderate amount</td>
<td>98</td>
</tr>
<tr>
<td>A great deal</td>
<td>34</td>
</tr>
<tr>
<td>A lot</td>
<td>40</td>
</tr>
<tr>
<td>NA</td>
<td>35</td>
</tr>
</tbody>
</table>

MS Eng. Johan Fanas Rojas
Survey Data

If you would like to learn more, you can read an upcoming journal publication from my colleague Sia!!
AV design comparison

Modifications of the autonomous shuttles at Western Michigan University

Parameters
- Wheelbase
- Battery type and configuration
- Access ramp availability
- Wheelchair securement
- Seating capacity
- Energy capacity
- Interior clear floor space

The intention of our analysis is to contrast the benefits of considering accessibility in the early design process of an autonomous vehicle

Off-The-Shelf Design
- $85,000

Campus Pilot Design
- $105,000

A new design is added to our analysis!!

$90,000-$95,000
Vehicle dynamics and suspension systems

- Vehicle dynamics is concerned with the movement of vehicles on a road surface

- A suspension system is a group of mechanical components used to connect the vehicle body and tires

  Types of suspension systems
  - Passive suspension system
  - Semi-active suspension system
  - Active suspension system

[Ikenaga, S., Lewis, F. L., Campos, J., & Davis, L., Active suspension control of ground vehicle based on a full-vehicle model (2000)]
Skyhook damping

Introduction

Methodology

Results

Conclusion

- The skyhook damping theory consists on a fictitious damper attached to the sprung mass and the stationary sky

- This method has been implemented in vehicles and it can be used for both semi-active and active suspension system

- The skyhook damping method, minimizes the vibration of the sprung mass by adding a variable damping force

[Tiwari, Aditya, Mahesh Lathkar, P. D. Shendge, and S. B. Phadke., Skyhook Control for Active Suspension System of Heavy-Duty Vehicles Using Inertial Delay Control (2016)]
Vehicle pitch and roll motion

Pitch and Roll 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 roll of a vehicle is the angular displacement about the longitudinal axis when cornering. The weight shifts left or right due to the centrifugal force while handling.

[Jazari, R. N., Vehicle roll dynamics(2008)]

[Campos, J., Davis, L., Lewis, F. L., Ikenaga, S., Scully, S., & Evans, M., Active suspension control of ground vehicle heave and pitch motions(1990)]
**Mathematical model**

**Ride comfort study**

- A mathematical model of a vehicle’s vertical dynamics was derived using Newton’s laws of motion

  - **Heave motion**
    \[
    \frac{d^2 z_h}{dt^2} = \frac{1}{m_h} \left( -F_{h,\text{air}} - k_{h,\text{air}} z_h - k_{h,\text{spring}} z_h - m_h g + F_{h,\text{road}} \right)
    \]

  - **Pitch motion**
    \[
    \frac{d^2 \phi}{dt^2} = \frac{1}{I_m} \left( k_{\phi,\text{roll}} \phi - k_{\phi,\text{torque}} \theta - J_{\phi,\text{moment}} \right)
    \]

  - **Roll motion**
    \[
    \frac{d^2 \phi}{dt^2} = \frac{1}{I_m} \left( k_{\phi,\text{roll}} \phi - k_{\phi,\text{torque}} \theta - J_{\phi,\text{moment}} \right)
    \]
## Simulation parameters

### Front Spring stiffness (N/mm)
- Off-The-Shelf Design: 14
- Campus Pilot Design: 19
- New Design: 21

### Rear Spring stiffness (N/mm)
- Off-The-Shelf Design: 28
- Campus Pilot Design: 22
- New Design: 24

### Roll axis Moment of Inertia (kg-m²)
- Off-The-Shelf Design: 276.70
- Campus Pilot Design: 347.34
- New Design: 363.00

### Pitch axis Moment of Inertia (kg-m²)
- Off-The-Shelf Design: 1346.36
- Campus Pilot Design: 2095.56
- New Design: 2139.92

### Sprung mass (kg)
- Off-The-Shelf Design: 1000
- Campus Pilot Design: 1065
- New Design: 1115

### Unsprung mass (kg)
- Off-The-Shelf Design: 20
- Campus Pilot Design: 20
- New Design: 20

### Front Tire- CG Distance (m)
- Off-The-Shelf Design: 0.81
- Campus Pilot Design: 1.14
- New Design: 1.25

### Rear Tire- CG Distance (m)
- Off-The-Shelf Design: 0.81
- Campus Pilot Design: 1.14
- New Design: 1.25

### Left Tire- CG Distance (m)
- Off-The-Shelf Design: 0.56
- Campus Pilot Design: 0.56
- New Design: 0.6

### Right Tire- CG Distance (m)
- Off-The-Shelf Design: 0.56
- Campus Pilot Design: 0.56
- New Design: 0.6

### Parameter/Off-The-Shelf Design/Campus Pilot Design/New Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Off-The-Shelf Design</th>
<th>Campus Pilot Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Spring stiffness (N/mm)</td>
<td>14</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Rear Spring stiffness (N/mm)</td>
<td>28</td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>Roll axis Moment of Inertia (kg-m²)</td>
<td>276.70</td>
<td>347.34</td>
<td>363.00</td>
</tr>
<tr>
<td>Pitch axis Moment of Inertia (kg-m²)</td>
<td>1346.36</td>
<td>2095.56</td>
<td>2139.92</td>
</tr>
<tr>
<td>Sprung mass (kg)</td>
<td>1000</td>
<td>1065</td>
<td>1115</td>
</tr>
<tr>
<td>Unsprung mass (kg)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Front Tire- CG Distance (m)</td>
<td>0.81</td>
<td>1.14</td>
<td>1.25</td>
</tr>
<tr>
<td>Rear Tire- CG Distance (m)</td>
<td>0.81</td>
<td>1.14</td>
<td>1.25</td>
</tr>
<tr>
<td>Left Tire- CG Distance (m)</td>
<td>0.56</td>
<td>0.56</td>
<td>0.6</td>
</tr>
<tr>
<td>Right Tire- CG Distance (m)</td>
<td>0.56</td>
<td>0.56</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### Damping Coefficients

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Off-The-Shelf Design</th>
<th>Campus Pilot Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front damping coefficient (Ns/mm)</td>
<td>1.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rear damping coefficient (Ns/mm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Ride comfort study
Ride comfort study

Generated Inputs

Introduction  Methodology  Results  Conclusion

Sinusoidal Input

Displacement (m)

Time (s)
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.

The acceleration of the vehicle at four different points were measured and used as our control variable.

Since we want to minimize the acceleration, a reference of zero was used for our control system.
• An ADAMS (Automated Dynamic Analysis of Mechanical Systems) model was developed to analyze the vehicles behavior during cornering and ride comfort

• ADAMS gives us a very good approximation of a vehicle’s kinematics because you can add the appropriate joints connecting two rigid bodies
A vehicle’s steering system is a group of components whose function is to keep the vehicle in a desired path.

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.

\[
\delta = \arctan\left(\frac{\delta_1}{L + \frac{R}{2}}\right) = \frac{\delta_1}{L + \frac{R}{2}}
\]

Representative Drive Cycle Development

Introduction

Methodology

Results

Conclusion

Energy consumption analysis

• A 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

• Battery configuration
  • Off-The-Shelf Design
    • Six 8V lead acid batteries in series
  • Campus Pilot Design
    • Four 12V iron phosphate batteries in series
  • New Design
    • Six 12V iron phosphate batteries in series

WMU driven route
### Methodology

#### Custom drive cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Off-The-Shel Design</th>
<th>Campus Pilot Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling resistance</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.311</td>
<td>0.311</td>
<td>0.34</td>
</tr>
<tr>
<td>Capacity amps-Hours (Ah)</td>
<td>176 (100 Hrs.)</td>
<td>110 (20 Hrs.)</td>
<td>167 (100 Hrs.)</td>
</tr>
<tr>
<td>Energy capacity per battery (kWh)</td>
<td>1.5</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Horsepower (kW)</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Min SOC (%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Front area of the vehicle (m²)</td>
<td>2.372</td>
<td>2.372</td>
<td>2.42</td>
</tr>
<tr>
<td>Rear axle ratio</td>
<td>14.76:1</td>
<td>14.76:1</td>
<td>14.73:1</td>
</tr>
</tbody>
</table>
• Some parameters were taken from the CAD model created in Solidworks

• Parameters
  • Front area of the vehicle
  • Moments of inertia
Results

• A ride comfort study was performed to study vehicle’s vertical dynamics

• The maneuverability of the three shuttles were analyzed by measuring the turning radius given the above specifications

• An energy consumption analysis was performed in order to compare the performance of all three battery packs
Ride comfort study

Introduction

Methodology

Results

Conclusion

- A ride comfort study of passive suspension system of three autonomous shuttles was performed
- An active suspension model was developed and compared the benefits of integrating this technology to the new design
- ADAMS/MATLAB co-simulation was performed, in order to combine MATLAB’s developed control system with our ADAMS model
Ride comfort study – Passive suspension system

Introduction

Methodology

Results

Conclusion

Step Input

---

**Vertical displacement vs Time**

- Off-The-Shelf Design
- Campus Pilot Design
- New Design

**Chassis vertical acceleration vs Time**

- Off-The-Shelf Design
- Campus Pilot Design
- New Design

---

MS Eng. Johan Fanas Rojas
Ride comfort study – Passive suspension system

Step Input

Pitch angle vs Time

<table>
<thead>
<tr>
<th>Angle (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-0.01</td>
</tr>
<tr>
<td>-0.02</td>
</tr>
<tr>
<td>-0.03</td>
</tr>
<tr>
<td>-0.04</td>
</tr>
<tr>
<td>-0.05</td>
</tr>
</tbody>
</table>

Time (s)

0 1 2 3 4 5 6 7 8

Sine Input

Roll angle vs Time

<table>
<thead>
<tr>
<th>Angle (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
</tr>
<tr>
<td>0.06</td>
</tr>
<tr>
<td>0.04</td>
</tr>
<tr>
<td>0.02</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-0.02</td>
</tr>
<tr>
<td>-0.04</td>
</tr>
<tr>
<td>-0.06</td>
</tr>
</tbody>
</table>

Time (s)

0 1 2 3 4 5 6 7 8
Ride comfort study – Passive suspension system

Methodology

Results

Conclusion

Rectangular Pulse

Vertical displacement vs Time

Chassis vertical acceleration vs Time

Off-The-Shelf Design
Campus Pilot Design
New Design

MS Eng. Johan Fanas Rojas
Rectangular Pulse

The new design performs better than previous designs because it increases stability and ride quality due to the increased wheelbase and track; in addition to the chosen suspension parameters!!
Ride comfort study – Active suspension system

Control system for active suspension system

- Acceleration in each suspension and used as a control variable for our control system
- To minimize the acceleration, we used a reference of zero for our summation block
Ride comfort study – Active suspension system

Introduction

Methodology

Results

Conclusion

**PID values for our control system**

- The PID controller was tuned manually using the trial and error method

- **Trial and error method**
  - Set the integral and derivative to zero and increase the proportional gain until it starts to oscillate
  - Change integral gain until steady state is reduced
  - Increase derivative gain until the system reacts quickly to its set point

<table>
<thead>
<tr>
<th>PID parameters</th>
<th>Wheel suspension system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Front left</td>
</tr>
<tr>
<td>Proportional gain (Kp)</td>
<td>2</td>
</tr>
<tr>
<td>Integral gain (Ki)</td>
<td>1</td>
</tr>
<tr>
<td>Derivative gain (Kd)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Ride comfort study – Active suspension system

Introduction ➜ Methodology ➜ Results ➜ Conclusion

Step Input

Vertical displacement vs Time

Vertical acceleration vs Time

Displacement (m)

Acceleration (m/s²)

Time (s)

Passive
Active

Passive
Active

MS Eng. Johan Fanas Rojas
Ride comfort study – Active suspension system

Introduction

Methodology

Results

Conclusion

Step Input

Sine Input
Ride comfort study – Active suspension system

Rectangular Pulse

**Vertical displacement vs Time**

**Vertical acceleration vs Time**
Ride comfort study – Active suspension system

Introduction

Methodology

Results

Conclusion

Rectangular Pulse

Key takeaways

Considering accessibility in the early design process + integrating an active suspension system to an autonomous vehicle:

- Improvements stability
- Improvements in ride quality
Ride comfort study – ADAMS/MATLAB Co-simulation

Control system for Co-simulation

• ADAMS model possesses all the kinematics of the actual autonomous shuttle

• ADAMS control toolbox was used to create an m-file and import it into MATLAB with the appropriate output and input variables
Ride comfort study – ADAMS/MATLAB Co-simulation

Co-simulation scenarios

- Pothole Road
- Sine Road
Ride comfort study – ADAMS/MATLAB Co-simulation

Introduction
Methodology
Results
Conclusion

Pothole Road

Passive suspension system

Active suspension system
Ride comfort study – ADAMS/MATLAB Co-simulation

Introduction

Methodology

Results

Conclusion

Pothole Road

Vertical displacement vs Time

Vertical acceleration vs Time
Ride comfort study – ADAMS/MATLAB Co-simulation

Introduction ➤ Methodology ➤ Results ➤ Conclusion

Pothole Road

Pitch angle vs Time

Roll angle vs Time
Ride comfort study – ADAMS/MATLAB Co-simulation

Introduction ➔ Methodology ➔ Results ➔ Conclusion

Sine Road

Passive suspension system

Active suspension system
Sine Road
Ride comfort study – ADAMS/MATLAB Co-simulation

Introduction  Methodology  Results  Conclusion

Sine Road

Pitch angle vs Time

Roll angle vs Time

Passive  Active

Time (s)

Angle (rad)

0 1 2 3 4 5 6 7 8

0 0.02 0.04 0.06 0.08

0 0.5 1 1.5

0 10^{-7}
Ride comfort study – ADAMS/MATLAB Co-simulation

Key Takeaways

1. Improved ride quality
2. Co-simulation provides insight on actual active suspension integration
3. New design performs better than previous designs and it’s cost effective
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 about the maneuverability of the vehicle.
Lateral dynamics – Turning Radius

Introduction

Methodology

Results

Conclusion

**Key Takeaways**

Negative impacts in terms of maneuverability!!

- The steering lock of the off the shelf design was determined by increasing the displacement of the steering rack until this turning radius was achieved.

- To determine the turning radius for the new design, we assumed the steering angle of the right and left wheel where same as the other models.

![Turning Radius Graph](graph.png)
Energy consumption analysis

- Battery configurations were changed due to increased clear floor space
- Decrease energy capacity
- Battery configuration for new design was assumed to our perception of how it should be

Discharge Time

Range
Using Autonomie and custom drive cycle, we ran a simulation until the battery was exhausted.

Autonomie is a simulation tool based on MATLAB and Simulink with a library of preloaded vehicle models and drive cycles.
Distance vs Time was plotted in order to observe the total distance traveled by the vehicle before the vehicle’s battery was exhausted.

Post-production modifications reduced approximately 14 miles of traveled distance.

**Key Takeaways**

Post-production modifications have negative impacts to the operating range and operating time!!
In order to give a contrast of the cost implications of our new design versus previous designs, a brief cost analysis was performed. The assumptions for our analysis are shown to the right.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Off-The-Shelf Design</th>
<th>Campus Pilot Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator salary ($/year)</td>
<td>$55,000.00</td>
<td>$55,000.00</td>
<td>$55,000.00</td>
</tr>
<tr>
<td>Purchase price ($)</td>
<td>$85,000.00</td>
<td>$105,000.00</td>
<td>$95,000.00</td>
</tr>
<tr>
<td>Maintenance per mile ($/mile)</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Cost of electricity ($/kWh)</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Total years</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Total passengers per day</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Total miles (miles/year)</td>
<td>9100</td>
<td>9400</td>
<td>8900</td>
</tr>
<tr>
<td>Vehicle depreciation rate first year (%)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Vehicle depreciation rate other years (%)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Operator annual salary raise (%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Electrical consumption (Wh/mile)</td>
<td>198.1</td>
<td>209.67</td>
<td>216.87</td>
</tr>
</tbody>
</table>
Cost Analysis

Introduction

Methodology

Results

Conclusion

Cost Analysis

Total Cost

Cost per passenger

Off-The-Shelf Design
Campus Pilot Design
New Design

Years

Cost ($)

Years

Cost per passenger ($/passenger)

0 5 10 15

80000 90000 100000 110000 120000 130000 140000 150000 160000

0 5 10 15

1.0 1.1 1.2 1.3 1.4 1.5 1.6

MS Eng. Johan Fanas Rojas
Cost Analysis

Average cost per passenger

- Off-The-Shelf Design
- Campus Pilot Design
- New Design

Shuttle design

Cost per passenger ($/passenger)

$1.18
$1.19
$1.20
$1.21
$1.22
$1.23
$1.24

$1.23
$1.23
$1.23
$1.23
$1.23
$1.23
$1.23
Summary

• A vehicle performance analysis was performed on three autonomous shuttle designs
  • Non-accessible autonomous shuttle
  • Post-production autonomous shuttle for wheelchair accessibility
  • Autonomous shuttle with the specifications we think should have for wheelchair accessibility (specifications which were considered in the early design process)

• In our ride comfort study, the new design performed better than previous models and it’s cost effective

• Integration of active suspension systems provide substantial improvements to stability and ride quality

• Increase in wheelbase has negative impacts to the maneuverability of the vehicle

• Post-production modifications have negative impacts to the energy consumption
• Post-production modifications are more costly than considering accessibility in the early design process.

• Taking accessibility as an after thought has negative impacts on the vehicle’s overall performance.

• Active suspension systems should be integrated in autonomous vehicles from factory because of the improvements in ride quality and stability.

• 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.
Future Work

• A stochastic optimization problem may be framed such that the design space and suspension tuning may be fully explored

• Accessibility considerations to provisions such as stop request buttons, emergency features, and user experience with communication to the autonomous shuttle

• An analysis to the cost and time impact of delayed implementation of accessibility to manufacturers and time to deployment

• Adding electrification to this research, in order to observe the costs reductions of ride sharing and having an accessible vehicle
Skyhook damping

• The skyhook damping theory consists on a fictitious damper attached to the sprung mass and the stationary sky

• This method has been implemented in vehicles and it can be used for both semi-active and active suspension system

• The skyhook damping method, minimizes the vibration of the sprung mass by adding a variable damping force

[Tiwari, Aditya, Mahesh Lathkar, P. D. Shendge, and S. B. Phadke., Skyhook Control for Active Suspension System of Heavy-Duty Vehicles Using Inertial Delay Control (2016)]
Energy consumption analysis – Range

- Distance vs Time was plotted in order to observe the total distance traveled by the vehicle before the vehicle discharged.

- Post-production modifications reduced approximately 14 miles of traveled distance.

Key Takeaways

Post-production modifications have negative impacts to the operating range and operating time!!
Cost Analysis

Introduction

Methodology

Results

Conclusion

Cost Analysis

Total Cost

Cost per passenger

Off-The-Shelf Design
Campus Pilot Design
New Design

Cost ($)

Years

Off-The-Shelf Design
Campus Pilot Design
New Design

Cost per passenger ($/passenger)

Years