Techno-Economic Analysis of Fixed-Route Autonomous and Electric Shuttles

Nick Goberville, Md Marsad Zoardar, Johan Rojas, Nicolas Brown, and Farhang Motallebiaraghi
Western Michigan University

Anthony Navarro Unity Technologies
Zachary D. Asher Western Michigan University


Abstract

This paper takes a realistic approach to develop a techno-economic analysis for fixed-route autonomous shuttles. To develop a model for analysis, the current state of technology was used to approximate three timelines for achieving SAE level 5 capabilities: progressive, realistic, and conservative. Within these timelines, there are four different increments for advancements in the technology laid out as follows: SAE Level 0 - human driver, SAE Level 4 - in-vehicle safety operator, SAE Level 4 - remote safety operator, and SAE Level 5 - no safety operator. These increments in the changes of the technology were chosen based on the trends in the industry. Various shuttle models were used based on different rider quantities and drive-train requirements (electric vs gas) in this analysis. This allows for further understanding of how these deployment plans will vary the cost for shuttles operating in high, mid, and low ridership demand environments. Additional drive-train comparison shows the savings based on the choice of electric vs ICE vehicles. Taking these parameters into consideration, simulations were run for the various vehicle models in the various ridership demand environments to produce the economic costs for each situation. It was found that in 15 years there is an economic savings of 72%, 68%, 43%, and 35% for small, medium, large, and extra-large shuttles, respectively if deployed with the conservative plan of becoming SAE Level 4 with an in-vehicle safety operator in 2 years, SAE Level 4 with a remote safety operator in 4 years, and SAE Level 5 in 8 years.

Introduction

Autonomous Vehicles (AVs) are quickly becoming a realistic technology to be deployed on a large scale in the near future. Companies like Waymo, Robotic Research LLC, May Mobility, NAVYA, and many others have already developed SAE level 4 autonomous vehicles operating in multiple locations around the United States, mainly as a shuttle service. A transition to the use of autonomous vehicles for shuttle and public transportation will result in many benefits including improved safety, improved vehicle efficiency, and much lower costs, which will be shown within this paper.

Additionally, when AV technology is combined with electric vehicle (EV) technology there are synergizing and compounding benefits such as improved transportation sustainability, reduced lifecycle costs, vehicle right-sizing redesigns, and they even unlock a new commercialization potential through decentralized vehicle ownership. These benefits are so profound that it has spawned a new field of engineering termed “mobility engineering” with many new degree programs in development at universities such as Wayne State in downtown Detroit, MI. Initial academic research addressing mobility engineering shows economic and societal benefits from fleet optimization, increased fuel efficiency, reduction of accidents, and reduction of cost.

Techno-economic analysis (TEA) is a technique that provides product lifecycle economic forecasting, return on investment, and process modelling via analysis of technical, economic, and current market details. EV (Electric Vehicle) technology is currently more mature and commercially available than AV technology and this EV technology has enjoyed numerous techno-economic analyses. Asher et al. showed how artificial neural network technology is capable of improved fuel efficiency with BHEV (Battery Hybrid-Electric Vehicles) leading to economic benefits. Gough et al. conducted an analysis on EV-based energy storage, Abas et al. which provided insights into the environmental impacts of EVs, and other studies conducted by Sakti et al., Englberger et al., and Neubauer et al., provide insight into the future of transportation sustainability via techno-economic analyses. Techno-economic analyses of AVs are sparse due to their interdisciplinary complexity and degraded technological maturity. Example studies include a study by Psaraki et al. which demonstrated how electric vehicles & intelligent transportation systems can reduce CO2 emissions and a study by Marletto et al. demonstrated how the automotive industry
will affect the self driving car revolution [21]. The shortcomings of these studies are that they are not combining the effects of AV and EV technologies for a combined economic benefit. To our knowledge no techno-economic analyses combining AV and EV technology exist.

The purpose of this novel study is to address the strong need for a robust in-depth, quantitative understanding of the financial outcomes caused by transitioning to the use of autonomous shuttles for fixed routes. The early adopters of autonomous shuttles have a common-sense understanding that using automated shuttle service will lower the cost of shuttle service operations, but there seems to be a lack of studies conducted placing quantitative values on this financial impact. Upon conclusion of this study, there will be numerical results showing the financial impact which is important and required for fixed route transportation managers to understand potential cost savings, returns on investment time, and more to promote adoption.

**Methods**

The following subsections will explain the process taken to conduct this TEA analysis. Overall, there were three modules used to develop it. These three modules are the Cost Model, Vehicle Model, and the Simulation Environment. The python code used for these modules can be seen for reference here, [22]. These three modules provide the necessary inputs to the cost analysis that allow for an understanding of how the transition to autonomous vehicles in shuttles affects the cost of these operations. A flow diagram of the process used is depicted in Figure 1.

**Vehicle Model Module**

**Key Parameters** The vehicles were divided into two categories based on their drive-train, Electric Vehicle (EV) and Internal Combustion Engine (ICE). As the costs for vehicles of different sizes vary greatly, such as operating, maintenance, and driver salary costs, we put them in four subdivisions based on the vehicle size: small, medium, large, and extra-large. To calculate the operating cost, the average mileage in a year each type of vehicle typically runs was used. Small vehicles usually run 12,000 miles a year. According to the average fuel price we calculated required fuel in gallon per year and calculated the total price of the fuel in a year. By dividing the price of fuel with the number of miles driven per year, we achieved the operating cost per mile. To calculate the maintenance cost, we have considered the average parts replacement costs, oil changes, and others required small maintenance costs. The average amount was divided by the number of average miles in a year in order to get the cost of maintenance of a vehicle per mile.

![Vehicle Model Module](image)

After reviewing our calculations with resources found, we tabulated our findings to use for the vehicle models module. The results are shown in Tables 1 and 2.

**Simulation Module**

The simulation was developed to generate realistic operating values for miles driven per day, riders transported per day, average rider wait time, and number of times the vehicle was full and unable to pick up a new rider. The simulated environment was built to mimic a given shuttle operating in a closed loop route in which the stops are priorly defined. The simulation contains three main object types: a rider, a shuttle stop, and a vehicle. The simulation assumptions are used to determine specific parameters used for each of these objects as well as the route characteristics.

![Simulation Module](image)
Simulation Assumptions The assumptions, along with their description, that needed to be defined prior to each run of the simulation are listed in Table 3. These parameters could be adjusted to accommodate various campus environments, e.g., increase/lower rider frequency and initial riders for high/low traffic environments, respectively.

Simulation Outputs The purpose of the simulation is to receive outputs for different driving environments, vehicles, and ridership demands. The values which are the number of miles driven per day, the number of completed rides per day, the number of riders which were unable to get on the shuttle due to it being at max capacity, and the wait time per rider. These values were used in the cost analysis as well as the ridership evaluation.

Cost Model Module
The cost model module’s purpose is to generate important values used to complete the cost analysis. The cost model uses values generated from the simulation as well as the given assumptions in order to compute the key calculations.

Cost Model Assumptions The assumptions used for the cost model play a key role in computing an accurate model for each vehicle. These assumptions can be seen in Table 4.

Key Calculations The core of the cost model is the calculations of the yearly cash flows for each value: purchase, maintenance, operation, and driver. These cash flows were calculated using equations (1) through (4).

\[
p = \text{purchase cost} \text{ ($)}
\]
\[
s = \text{distance driven per year} \text{ (miles)}
\]
\[
d = \text{driver salary} \text{ ($/year)}
\]
\[
r = \text{inflation rate} \text{ (%/year)}
\]
\[
t = \text{years} \text{ (years)}
\]
\[
m = \text{maintenance cost} \text{ ($/mile)}
\]
\[
op = \text{operation cost} \text{ ($/mile)}
\]
\[
A = \text{A-kit maintenance cost} \text{ ($/mile)}
\]
\[
B = \text{teleoperation kit maintenance cost} \text{ ($/mile)}
\]
\[
A_{\text{init}} = \text{binary identifier if A-kit is installed}
\]
\[
B_{\text{init}} = \text{binary identifier if teleoperation kit is installed}
\]
\[
d_{\text{rate}} = \text{percent of driver salary} \%
\]

Cost Analysis
The cost analysis was the final step to achieve an understanding of how the transition to autonomous shuttles will financially impact this industry. The cost analysis provides us detailed plots and information about the financial characteristics of each vehicle in any given simulation environment. Four different operating modes were analyzed in three various hypothetical deployment scenarios. These variations are explained further in the following subsections.

Driving Modes Four different driving modes were used in this analysis to see the variation in various deployment situations. The four modes allow us to understand the financial impacts and limitations for different ways of deploying autonomous vehicles.

Normal Operation The normal operation mode would be the type of shuttle that is used today. This is a shuttle that is driven 100% by a human and would be considered SAE level 0 autonomous.

Autonomous Operation with a Safety Operator The autonomous operation with a safety operator mode would be a shuttle that has the common level of autonomy available today for operating on an enclosed campus (SAE level 4) with a safety operator present. The reason a safety operator is present in any deployment today is because of regulations and confidence levels of the companies deploying.
these vehicles. In all deployments happening today, there is almost always a safety operator.

**Autonomous Operation with a Remote Safety Operator** The autonomous operation with a remote safety operator mode is added to introduce a method of transitioning from autonomous with a safety operator to fully autonomous operation while still allowing human intervention if necessary. There are multiple companies today deploying vehicles with this capability and it is called teleoperation. Teleoperation will likely play a key role in the transition from SAE level 4 to level 5 automated shuttles [23, 19].

**Fully Autonomous Operation** The final mode, fully autonomous operation, is the ideal mode of operation that provides the most insight as to how transitioning to fully autonomous shuttles will financially impact this transportation method. This mode is considered to not need a driver at all and the vehicle is able to drive 100% on its own.

**Deployment Scenarios** Since the purpose of this cost analysis is to study how the transition to fully autonomous vehicles impacts the cost of shuttle operations and fully autonomous vehicles do not yet exist, a few scenarios were created to depict different methods of deployment. Each scenario gives a different insight that allows us to see which methods of deployment are better than others. Scenario 1 is the most conservative estimate with a transition to autonomous with a safety operator at year 2, a teleoperation upgrade at year 4, and a fully autonomous upgrade at year 6. Scenario 3 is the most progressive estimate and scenario 2 is in the middle of scenario 1 and 3. Table 5 provides an overview of each scenario conditions.

## Results and Discussion

The results shown are the plots generated from the cost analysis module. These plots compute various types of analysis of the vehicle cost models using the simulation results. The three main parts of the cost analysis is the costs associated with each vehicle which Figures 2 and 3 show the YTD costs and cost per mile, respectively, then the ridership evaluation seen in Figure 4, and finally the deployment scenario analysis in Figure 5. These plots combine to complete the total cost analysis.

The year-to-date results show the total amount of cost paid up until each year. This plot visualizes the total cost for each vehicle model for each mode of driving. The small and medium sized shuttles both resulted in very similar outcomes since they both have similar costs for each parameter. There becomes a large increase in total costs once the shuttles expand to large and extra-large sizes. This is due to the increase in operating and maintenance costs.

A key takeaway from Figure 2 is that no matter what sized vehicle, using both an electric vehicle and an autonomous vehicle results in the greatest reduction in total cost after 15 years. The average break even point for the electric vehicle in 2 years for the small and medium shuttles, 2.5 for the large shuttle, and 6.75 years for the extra large shuttle. This is caused by the drastic increase in battery size and the increase in cost of maintaining these large shuttles.

The cost per mile bar plot (Figure 3) is provided to demonstrate the relative cost for each mile driven for each driving mode and each vehicle size. It is clear from viewing this plot...
that the fully autonomous shuttle reduces the cost of running a shuttle service greatly. This is due to the fact that this mode is completely eliminating the cost of the driver since there is no need for a driver to be in the vehicle. As this mode of driving is very optimistic for the year of 2020, the mode of operating an autonomous vehicle with the remote fleet manager is included to demonstrate how this also greatly reduces the cost of shuttle services.

Figure 4 provides insight into the ridership performance of the various sized shuttles and also to the reduction in cost for the various modes of driving introduced. One thing to mention here is that just as in Figure 3, there is a spike in cost for the autonomous mode with a safety driver present, and this is caused by the assumption that the safety driver will be receiving a 10% raise as mentioned in Table 4. Additionally, the autonomous shuttle requires more expensive hardware/software to be installed onto the vehicle causing the price of the shuttle to also greatly increase. However, just as in Figure 3, Figure 4 provides evidence that the push for autonomous shuttles is very cost effective once the ability to operate fully autonomous is available.

Because the increase in operation for the autonomous vehicle with a safety driver is present in the results so far, a depiction of three possible deployment scenarios were suggested and the resulting year-to-date costs are plotted in Figure 5. These results provide an insight into a few realistic approaches to having a fully autonomous shuttle varying the time it would take to get an autonomous shuttle with a safety driver, an autonomous vehicle with a fleet manager, and then finally a fully autonomous vehicle.

### Conclusions

This study has provided insight into how the intersection between electric and autonomous vehicles can provide a great deal of cost savings for shuttle service applications. From these results, it shows that electric vehicles are 28% more expensive to purchase for the small shuttle, 7.5% for the medium shuttle, 25% for the large shuttle, and 42.8% for the extra-large shuttle. However, since EV's have much lower operating and maintenance costs, after 2 years for the small and medium shuttles, 2.5 for the large shuttle, and 6.75 years for the extra large shuttle, the EV will break even with the ICE shuttles, hence, saving money from that point on. Since transportation shuttles typically last at least 12 years, there is plenty of time for cost savings, leading to $18,111.10 for small, $17710.93 for medium, $17,132.96 for large, and $45,270.22 for extra-large after 15 years of operation. Due to the extra purchase costs of the large battery and electric demand, the large electric shuttle shows to be less cost effective based on these findings. Electric shuttles are optimal for smaller sized vehicles.

Autonomous operations also show to result in great reductions of cost over time. As fully autonomous vehicles are not yet deployable today, three deployment scenarios were analysed which show a few possible routes to getting to a fully autonomous shuttle and how following some of these paths will still result in great cost savings. If following scenario 1 in Table 5, there would be a 48.94% and 51.16% reduction in cost for small electric and gas shuttles, respectively, 50.26% and 48.12% in medium electric and gas shuttles, 42.36% and 40.69% in large shuttles, and 33.48% and -2.85% in extra-large shuttles after 15 years of operation. From the results in Figure 5, it is clear that the quicker a transition to fully autonomous vehicles is made, the larger the cost savings are, except for extra large ICE shuttles which further drives reason for transition to EVs. As the technology becomes more advanced, the availability of level 5 autonomous will be increased and the option to deploy level 5 will be available. Even with the technological limitations, like operating in adverse weather [24], the act of pushing the boundary of normality by using an autonomous vehicle with a safety operation with plans to transition to a fleet manager followed by fully autonomous will result in great cost savings as mentioned in the above table.

Putting all of this together, to achieve the greatest amount of cost savings for any type of shuttle operation (small, medium, large, extra-large sizes), there will be positive outcomes if a fully autonomous, electric shuttle is selected as the vehicle of choice. With technology today, people have the ability to deploy level 4 autonomous shuttles on fixed routes, so implementing this method of operation will result in cost savings assuming there is the possibility of transitioning to a remote fleet manager of the network of shuttles. It is recommended that any shuttle service use an electric shuttle with autonomous capabilities using remote fleet managers as this is possible due to technologies companies like DriveU and Designated Driver have developed for remote operations. This method would allow a seamless transition to fully autonomous.
operations and utilize both the cost savings benefits from utilizing electric vehicles and autonomous operations.

If the push to further advance our mobility technologies even if they are not level 5 capable today will still prove to have significant economic gain in the long term because this push for advancing technologies allows the technology to grow at a more accelerated rate than if the more economic approach for this moment in time is taken. If advanced automation technology combined with electric vehicles is slowly adapted into transportation shuttles, there will be cost reduction of up to 50.26% in 15 years of operation.

References


Contact Information

Zachary D. Asher, PhD, 
Mechanical & Aerospace Engineering Dept., 
1903 W Michigan Ave., Kalamazoo, MI 49008-5314, USA, 
zach.asher@wmich.edu

Nick Goberville, 
Mechanical & Aerospace Engineering Dept., 
1903 W Michigan Ave., Kalamazoo, MI 49008-5314, USA, 
nicholas.a.goberville@wmich.edu
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Definitions/Abbreviations

AV - Autonomous Vehicle
EV - Electric Vehicle
ICE - Internal Combustion Engine
TEA - Techno-Economic Analysis
BHEV - Battery Hybrid-Electric Vehicles