A Design Concept for Improving Local Transportation Systems & A Device to Reduce the Spread of Hospital-Acquired Infections

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

James Groves, Department of Engineering and Society

Engineering Design of a Solution Concept:

A Design Concept for Improving Local Transportation Systems & A Device to Reduce the Spread of Hospital-Acquired Infections

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Executive Summary

Transportation systems have been integral to the development of modern society as they have greatly facilitated the movement of people and goods. At the same time, they have led to the deterioration of the environment by generating air pollution and greenhouse gases. The achievability of the widespread adoption of environmentally friendly technologies has increased in the past few decades so sustainability must be emphasized in current and future transportation systems. The first portion of this report produces a design concept for sustainable transport in the Charlottesville area. Namely, it provides a stepping stone for future capstone groups that may take up this project. Our framework for a sustainable transportation plan indicates that any solution should ensure that Albemarle County emissions in 2030 are reduced by 45% when compared to 2010 levels and that the University of Virginia reaches its goals of carbon neutrality by 2030 and being fossil fuel-free by 2050. The three pillars of our particular plan include a marketing campaign, countywide electric bus implementation, and bus rerouting. However, the rest of my group could not continue this project so the viability of this plan could ultimately not be determined.

I subsequently joined another capstone group that worked to reduce the likelihood of hospital-acquired infections arising from wastewater sources. Hospital-acquired infections merit investigation given their ability to develop in a health-care setting, which is one in which people expect to receive medical treatment. Furthermore, the microorganisms that cause such infections are typically drug-resistant and are continuously evolving to defend themselves against existing antimicrobials. The characteristics of these infections mean they must be prevented from reaching patients. The second portion of this report produced a design for the construction and testing of a device that reduces the spread of hospital-acquired infections from wastewater sources, specifically sinks. This device employs ultraviolet germicidal irradiation to kill or inactivate bacteria in plumbing traps. What distinguishes this device from other solutions is a quartz glass that filters ultraviolet C radiation at the bottommost part of the sink U-bend to irradiate bacteria in the wastewater there to prevent them from “climbing” the pipe and infecting patients. Ultimately, this device could not be prototyped due to the COVID-19 pandemic.

The distinction between the two works will be clear as all information pertaining to the second work will start with the header: “Exploration of a design concept.” Due to the incompleteness of both projects, I would like to draw attention to the sections: “Transition between projects,” “Reflections on design,” and the appendix. These three sections illustrate the main takeaways from attempting both projects.

Transportation is essential for the functioning of society but maintaining the status quo with regard to environmental standards is unwise. Similarly, maintaining the status quo with regard to hospital-acquired infections can give rise to microbes with antimicrobial resistance. Given that the combined body of work developed solutions for problems that were ultimately created out of the solutions to prior problems, consequential thinking must play a bigger role in design thinking.

Definition of the Challenge Space

Challenge Definition

Identifying the Challenge

The time to address climate change is now. Transportation is a sector that is of interest due to it being one of the largest contributors to pollution and greenhouse gas emissions. For the purpose of analyzing measurable data, my group will focus research efforts on the city of Charlottesville, Virginia and the surrounding Albemarle County. We will investigate the current state of transportation in these areas with two aims: finding ways to help the county transition to renewable energy as the main source of fuel for transportation and making the transportation system more efficient, reliable, and accessible for residents. Narrowing our analysis to this area can allow for a solution framework that can be adapted with respect to other communities.

Root Causes of the Challenge

Transportation is an inconspicuous but essential aspect of our daily routines. However, the transportation industry has a significant impact on the environment. In the United States, transportation forms 29% of total greenhouse gas emissions, with 82% of these emissions coming from road vehicles. Collectively, individual cars have the largest impact since light-duty vehicles are responsible for 59% of total emissions in the United States as can be seen in the figures below from the Environmental Protection Agency (EPA).

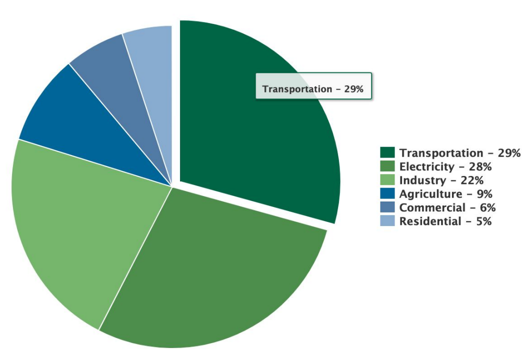


Figure 1.1: U.S. Transportation Sector Emissions by Sector

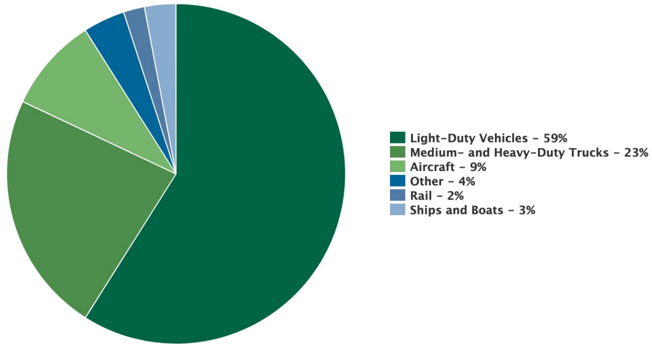


Figure 1.2: U.S. Transportation Sector Emissions by Source

While it is known that greenhouse gases negatively impact the environment, convenience and availability make it extremely difficult to renounce such modes of transportation. But the amount of energy needed for transportation alone is significantly rising globally and most of this increase stems from a rise in energy consumption due to passenger travel as non-OECD nations surpass OECD nations as seen in the figure below.

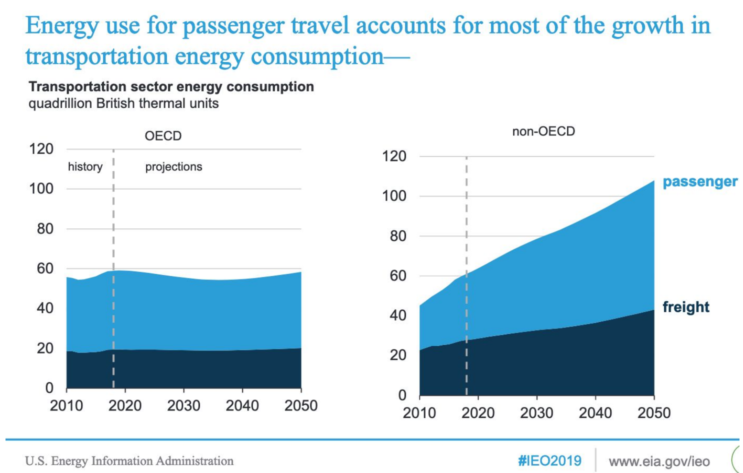


Figure 1.3: Transportation Energy Consumption - Passenger Travel Growth

Thus, establishing a solution that can work in the United States, an OECD country, will indicate to non-OECD countries that sustainable transport can be promoted without compromising economic growth.

Synthesis of Knowledge

After conducting our research, it is clear that there are a number of challenges regarding transportation in Charlottesville and Albemarle County. First of all, with the exception of personal electric vehicles, the area is still in the progress of transitioning to renewable energy. Unfortunately, there is still some resistance. A researcher at the Virginia Transportation Research Council mentioned that an anonymous manager at Charlottesville Area Transit (CAT), a public bus service for the greater Charlottesville area, was hesitant to switch to electric buses in the near future because of the costs associated with installing infrastructure and having to maintain vehicles (Peter Ohlms, interview, 2019). However, there are a number of organizations and institutions that are researching the affordability of electric vehicles and they will be identified along with the other stakeholders below.

The other main challenges relate to accessibility and efficiency for public transportation. Cars remain the main source of transportation for most people in Charlottesville and Albemarle. While the shuttle and rideshare services in the area are expanding, there is still more that can be done to reach a greater number of people. Currently, commuting into Charlottesville can be difficult for employees as they must find a way to enter the city either by car or bus and then take the CAT or University Transit Service (UTS), the free bus service provided by the University of Virginia (UVa), to their specific work location.

Harms or Benefits from Challenge

Discovering and creating transportation solutions in Albemarle and Charlottesville will allow my group to help commuters receive faster and more efficient transportation. With improved public transportation, residents can have lower transportation costs since they will not need to pay for gas or personal parking spots. In addition, addressing this challenge will expedite the process of transitioning to renewable energy for the transportation sector. Reducing emissions from vehicles will have a large impact in slowing climate change. Long-term benefits could also be expected as there are many students in the area, who could be influenced to make future commuting choices based on the changes they see when they are younger (Shannon et al, 2005).

It may be difficult to implement certain solutions without a sufficient source of government funding or with a public perception that new systems may not work or could be inconvenient. In order to address these potential obstacles, my group will ensure that our solutions have a strong basis for implementation ranging from efficiency to daily accessibility. Consequently, they can gain sufficient support to be eligible for allocated funds to improve quality of life for both residents and workers in the area.

Key Stakeholders

The key stakeholders involved are the largest institutions and the employees of the largest workforces in Charlottesville including UVa, the UVa Health System, county and city governments, and local schools. Relevant public transportation authorities include: JAUNT (another local service), CAT, and UTS. Renewable energy companies (Proterra, Fermata Energy), climate and sustainability organizations (Charlottesville Climate Collaborative, Generation 180), and private rideshare companies will also play a role in providing possible transportation solutions for the residents of Charlottesville and Albemarle County. Our solutions must take into account the motives of these stakeholders.

Measurable Challenge and Design Requirements

We will focus on measuring the following aspects related to our challenge space:

- Quantitative effects of climate change
- Proportion of transportation energy and emissions compared to other end-use sectors
- Albemarle and Charlottesville population statistics
- Albemarle and Charlottesville commuting trends
- Number of employees in major local companies and institutions
- Movement of employees from residences to work locations
- Commuting times for employees
- Transportation modes available and route patterns

Reflection and Research

Individual Reflection

Survey of the Problem Area

There are many reasons why public transit as it stands currently is ineffective in terms of efficiency and sustainability. However, it is unclear what most impedes progress in this area. Researching current problems in the field allows for targeting the most important issues. Speaking with experts in the field would also better inform us of the current situation. Lastly, it might be worth investigating other sustainable transport systems in the nation or internationally to examine their advantages and disadvantages.

Relevant Questions

- What are the most pressing issues in the field of sustainable transportation?
- What issues should be researched first?
- Who would be the best contact for information in this area?
- What are some examples of success in this area?

Overview of Cars

Personal vehicles have been the predominant form of transportation for Americans for over a century. The majority of cars in use run on an internal combustion engine that depends on the combustion of fossil fuels. Electric cars have become a viable alternative in recent years given that they produce less noise and emissions compared to conventional cars. Cars have costs and benefits to their use as well. Their costs to an owner include acquisition, payment of interest, repairs and maintenance, fuel, and insurance. The costs to society include road maintenance, land use, air pollution, and road congestion. Traffic collisions likely cause a large number of injuries and deaths worldwide. However, their benefits include transportation that is on-demand, increased mobility, and greater convenience. While cars certainly have their shortcomings, they are entrenched in modern society as the archetypal form of personal transportation.

Overview of Bikes

Bicycling is a form of transportation that is of interest because of its effectiveness and efficiency in travelling short distances. When compared to motorized vehicles, bicycling has such benefits as physical exercise, simpler parking, and greater maneuverability. Bicycling also offers noticeable benefits for environmental sustainability given that it can result in lower consumption of fossil fuels, less pollution, and much less traffic congestion. Regularly bicycling as a primary form of transit can lead to lower financial costs to the user as well as to society at large. However, it does not come without its shortcomings. Bicycling requires a basic level of fitness, is incapable of transporting multiple passengers, has less protection against both weather conditions and crashes, and requires longer travel times especially for longer distances.

Group Reflection

Most important is the movement of people in Charlottesville and the surrounding areas that form Albemarle County. As such, it would be prudent to study the populations of the largest employers and investigate their daily commutes in terms of distance and mode of transportation.

Understanding the Focus Population

In order to fully understand our challenge area, my group must gain a better understanding of the residents of Albemarle County and their daily commuting patterns in and out of the city of Charlottesville. What follows are questions that merit investigation. How does the population of Charlottesville compare to the population of surrounding Albemarle County? What groups of people currently take similar routes of transportation? What does the typical daily commute look like for employees for major institutions?

Further Developing Transportation Through Urban Planning

Developing solutions to help public transportation become more sustainable, efficient, and accessible requires an analysis of the types of vehicles and mass transit available to residents in Charlottesville and Albemarle County. This analysis will let my group determine the current state of transportation and understand what the involved entities desire. For the types of transportation my group investigate in our external research, my group wants to gain a better understanding of the following factors:

- Rider population on a daily or regular basis
- Mode of travel
- Vehicle miles traveled on a daily or regular basis
- Traffic congestion

- Relative accessibility to the public in terms of:
    - Location
    - Cost
    - Convenience
    - Public awareness

Gaining Insight From Stakeholders

In addition, my group will work with the potential stakeholders involved in transportation design for Albemarle County and gain insight from cities and universities with experience using electric mass transit. Additionally, we will connect with organizations that share a common goal of addressing climate change such as the Charlottesville Climate Collaborative and those that can provide data on the transit that occurs within the county such as the Virginia Transportation Research Center and UVa Parking and Transportation.

External Research

Climate Change Effects in Virginia

We chose this challenge space because climate change is already having profound effects on a global level that will soon be seen in Charlottesville if they have not been already. One dangerous effect is the continuous increase in temperature. In 2050, Charlottesville is predicted to have temperatures greater than 105 degrees for 44 days or nearly an eight of the year (Virginia's Climate Threats, 2019).

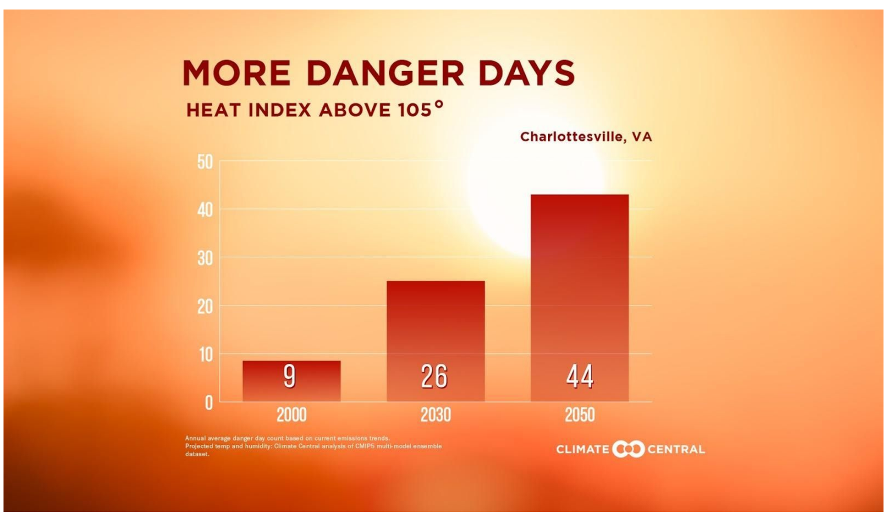


Figure 1.4: Heat Index Above 105 Degrees - Charlottesville

The greater frequency or longer duration of heat waves will increase a variety of health risks. While heat exhaustion and stroke are commonly known results of heat waves, there is evidence to suggest that people are more vulnerable to general health issues in extreme temperatures. It has been recorded that there is a clear association between emergency room visits in Charlottesville and heat waves; many of the visits could be linked to problems exacerbated by exposure to high temperatures (Davis, 2018).

The Movement for Sustainable Transportation

Other countries are already addressing climate change through the transportation sector. Many countries in Latin America are already taking action to address this issue by switching to electric vehicles. Countries such as Chile are planning to rely solely on electric energy for transportation in the next 20 years. Over the next five years, it is predicted that Latin American cities will be purchasing over 5,000 electric buses per year (Gallucci, 2019).

However, the current leader in making the switch to renewable energy regarding electric buses is China. In 2018, the contrast between the U.S. and China was staggering; China accounted for 99% of electric bus purchases while the U.S. had only purchased 300 electric buses (Evers, 2019). At the same time, it must be noted that other countries may have experienced the effects of climate change to a greater degree than the United States, which led to the need for immediate change. For example, China has experienced such poor air quality in cities that climate change has become a major health concern and a priority issue deemed as requiring government intervention (Evers, 2019).

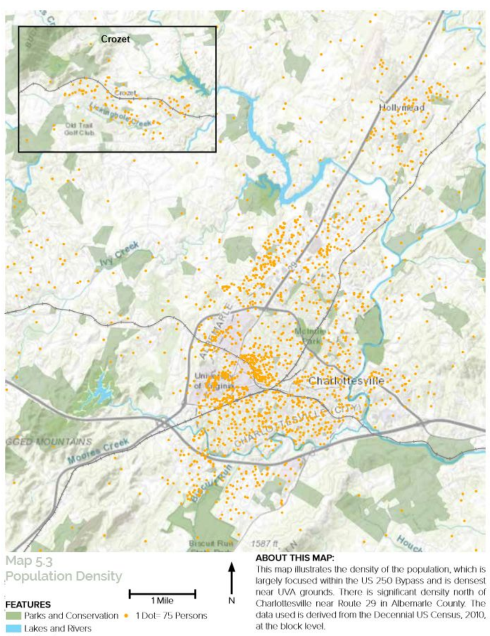
An Overview of Charlottesville and Albemarle County, VA

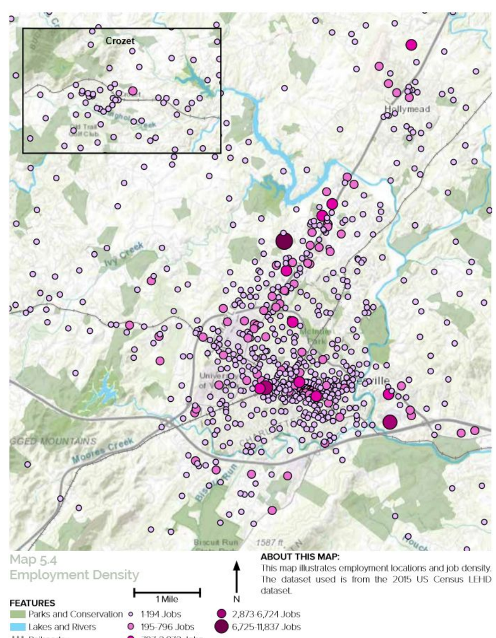
Albemarle County is a county in central Virginia has a land area of 720.70 square miles and as of July 1, 2018, is estimated to have approximately 108,718 total residents. There are roughly 40,015 households and 61% of the population is in the civilian labor force with an average time of 21.9 minutes to travel to work on a regular basis (U.S. Census Bureau, 2018). As can be seen, the majority of the population relies on vehicle transportation for at least a part of their daily commute.

The city of Charlottesville is encircled by Albemarle County. The city proper has a population of 48,019 people with a density of 4,599 people per square mile. 82% of employees who work in Charlottesville commute from outside of the city, while 11,000 residents commute out to different areas. Less than half of the employees commuting into Charlottesville for their work are from Albemarle, which means that a significant portion of employees are traveling long distances on a daily basis (Charlottesville ... Population, 2019). For this reason, there must be public or accessible transportation that extends beyond Albemarle in order to ensure efficiency and reduce the use of personal vehicles. With fewer cars on the road, the city can prevent traffic congestion and lower emissions.

Understanding the Population

Understanding population density and makeup is also of importance as it provides an understanding of the demand for infrastructure and where community members live. The following maps from the Thomas Jefferson Planning District indicate population and employment density.





<u>Figure 1.5: Visualization of Population (left) Density</u>

<u>Figure 1.6: Visualization of Employment (right) Density</u>

Population appears to be most concentrated in the city of Charlottesville with a significant density north of the city along US Route 29, while employment density data reveals that most employment locations are in downtown Charlottesville with a significant presence north of the city along U.S. Route 29.

Transportation Overview in the City of Charlottesville

Charlottesville is located in the Piedmont region of Virginia and is central with regards to southwest Virginia, central Virginia, and northern Virginia. This central location is evident when looking at the various transportation infrastructure that services Charlottesville. Highway systems include interstate I-64, which runs east-west, and the US Routes 29 (north-south) and 250 (east-west). Additionally, the average commute time for Charlottesville residents is 17 minutes (Business Data, 2019).

Common Destinations and Points of Origin for Commuters

Examining destinations can provide a better understanding of what modes of transportation and routes are frequently used. From Charlottesville, the vast majority of workers commuted to surrounding Albemarle County while a significant minority commuted to areas such as northern Virginia (Fairfax County and Arlington) or central Virginia (Henrico County and Richmond city) (Business Data, 2019).

Table 1.1: Top 10 Places Workers are Commuting to from Charlottesville in 2014

Top 10 Places Workers are Commuting To:

Albemarle County, VA	5,966
Fairfax County, VA	579
Henrico County, VA	380
Richmond city, VA	282
Chesterfield County, VA	224
Harrisonburg city, VA	211
Staunton city, VA	147
Prince William County, VA	138
Arlington, VA	137
Augusta County, VA	132

Given that the Charlottesville labor force numbered approximately 26,000 in the 1st quarter in 2019, it is clear that the majority of the workforce works within city limits. Point of origin is also of interest as it illustrates the percentage of workers who are city residents. As can be seen below, workers are primarily commuting from Albemarle County with most of the rest commuting from neighboring areas. This shows that there is little long distance commute to Charlottesville.

Table 1.2: Top 10 Places Workers are Commuting From in 2014

Top 10 Places Workers are Commuting From:

Albemarle County, VA	12,919
Fluvanna County, VA	2,401
Greene County, VA	1,409
Louisa County, VA	1,121
Augusta County, VA	1,039
Nelson County, VA	797
Waynesboro city, VA	717
Orange County, VA	605
Fairfax County, VA	573
Virginia Beach city, VA	494

Source: Bureau of Census, OnTheMap *Application and LEHD Origin-Destination Employment Statistics, 2014*

Commuting at UVa

The majority of transportation emissions at UVa stem from staff and faculty commuting as can be seen in the figure below (Petit, 2019).

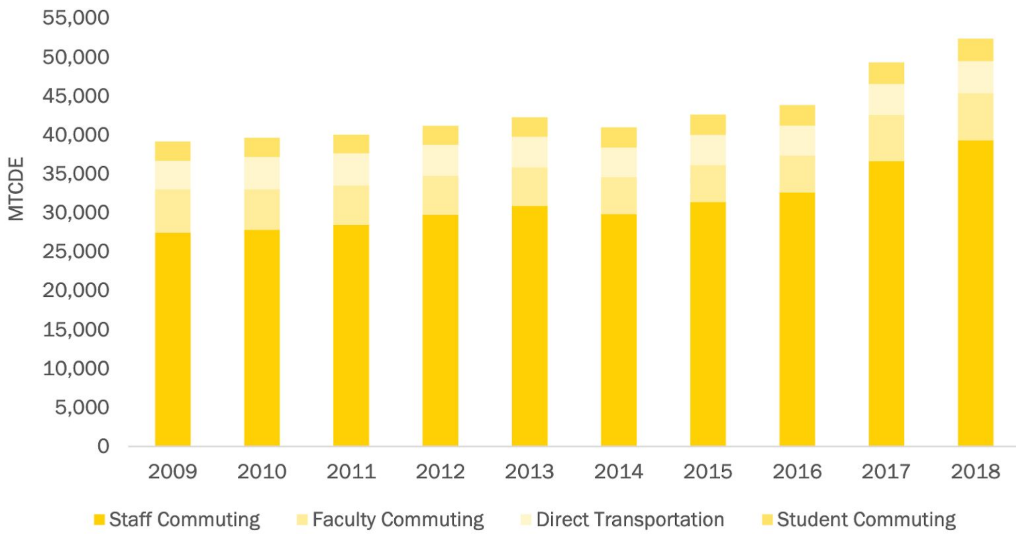


Figure 1.7: UVa Transportation Emissions Trends Measured in MTCDE (Metric Tons of Carbon Dioxide Equivalent)

UVa employees use a combination of personal vehicles and public transportation to come to work. For those taking cars, they must purchase a permit. There are two additional rideshare services that help UVa employees with their daily commute. CavPool is a program that encourages employees to carpool in order to access a number of perks ranging from discounted permits to reserved parking spaces. Vanpool is an additional program that currently provides two vans for up to 15 passengers each commuting from Richmond to UVa for work (Rideshare, 2019). In order to use the service, employees must live at least 35 miles away from the University and pay a monthly rate. Because this program could apply to a much larger proportion of UVa staff, my group can further explore how Vanpool can expand its services or add additional routes in the future (Rideshare, 2019).

With over 12,000 employees, the University of Virginia Health System is one of the largest employers in Charlottesville and the surrounding areas of Albemarle County (Facts & Figures, 2019). Employees who come to work can purchase permits for parking from UVa Parking and Transportation and are allowed access to parking lots near John Paul Jones Arena. At the same time, there are shuttles that provide transportation for both patients and workers to a number of nearby locations in the medical area with parking available (Shuttle Service, 2019). These locations include the Medical Center, the Fontaine Research Park, and the Northridge Medical Park.

Examining Common Modes of Transportation:

Buses

Buses are a major part of this challenge space due to the fact that they save energy by reducing the number of individual trips. In Albemarle, there are three major bus services that provide the majority of local transportation to county residents and employees: JAUNT, CAT, and UTS.

While perhaps less commonly known in the Charlottesville community relative to the other two bus services, JAUNT is the largest bus service in the region with regard to the land area it covers and its multiple goals to provide "rural, commuter, and paratransit services within Albemarle County" (Public Transit & Commercial Travel, 2019). CAT is the major bus service that operates in the city but also surrounding areas that are part of the county. According to the CAT's most recently published report in 2013, the system was preparing to take advantage of the following opportunities in the future:

- "Redesign transit routes to better serve transit demands."
- "Provide more direct service."
- "Increase stop spacing."
- "Develop a new outer transfer center."

Lastly, the University Transit Service (UTS) is the main source of public transportation throughout the University of Virginia. Major stops include the UVa Chapel, UVa Hospital, Scott Stadium, and the Barracks Road Shopping Center.

In terms of the UTS system, the routes are accessible to students and workers, so the main goal for improving the system would be transitioning to electric energy. Regarding the other two bus systems, my group will explore ways in which they can reach a greater segment of the growing population either by generating alternative routes, allocating buses at certain times, or combining them with different forms of transportation.

In order to establish a better bus system, my group must explore possible methods of obtaining funding. At the University of Georgia and the University of Utah, the schools received grants to purchase electric buses (Davidson, 2016). Chad Larsen, Associate Director for Commuter Services at the University of Utah, emphasized in an interview that the success of two electric buses they purchased stemmed from their ability to partner with Park City, a nearby city, to make the funding and the overall initiative possible.

Rail

With regard to Amtrak, there is currently a disconnect between the multimodal Downtown Transit Center and the Charlottesville Union Station, causing rail to be an inconvenient mode of commuting (Jones, 2014). However, buses connect these hubs to areas in the University of Virginia and the local Charlottesville community, making it a realistic option for more infrequent travel. In regards to long-distance travel, Amtrak is a widely used alternative to cars, allowing the convenience of skipping heavy I-95 traffic at peak times, and connecting major cities all the way to Chicago, making transfers to other areas also possible.

Cars

The American Community Survey (ACS) is conducted by the United States Census Bureau and publishes, among other statistics, detailed estimates on commuters' means of transportation to work. However, this data does have some limitations. It is limited to workers 16 years and older and instead of collecting data based on the locations of their jobs, it is collected based on their residences. It should also not be confused with the Census, which counts people and households every ten years, as ACS statistics are estimated on a 5-year basis using a representative survey sample. These ACS statistics reveal that cars are still by far the preferred mode of transportation but other modes of transportation did see noticeable increases between the two time periods of 2008-2012 and 2013-2017 were working at home or walking (American Community Survey, 2018). The other modes of transportation did not show significant change.

The Charlottesville Climate Collaborative (C3) is working with local businesses to reduce car emissions. One way companies can accomplish this goal is by offering incentives to employees who find alternative ways to get to work such as by walking or biking. For example, managers could offer rewards such as free lunches to encourage workers to bike or ride on the CAT. In a phone interview, Claire Habel, Commercial Program Manager at C3, highlighted the Better Business Challenge, a recurring event where businesses complete energy assessments and work to reduce pollution in a number of sectors including transportation. During last year's challenge, businesses reduced carbon dioxide emissions by 1823 tons. The Collaborative also helped lead an event recently in which electric car owners brought their own electric cars to let people test the vehicles and ask them about their experiences. Habel emphasized that this event was a success because it encouraged the public to hear personal testimonies while also giving them the opportunity to have first-hand experience driving the electric cars themselves.

E-scooters

E-scooters are a relatively new addition to the transportation scene in the Charlottesville area. They appear to be increasing in popularity, led by scooter-sharing services such as Lime and Bird. According to Mr. Ohlms of the Virginia Transit Research Center, the city of Charlottesville is currently under the pilot program for Lime e-scooters. Some students also appear to be using personal scooters, e-scooters and skateboards (electric/ manual), though these appear to be a small fraction.

Bicycles

Also relevant in the local biking community is a service provided by The University of Virginia Department of Parking and Transportation, University of Virginia Bike Share or UBike. UBike allows for temporary use of a bicycle in the system area below:

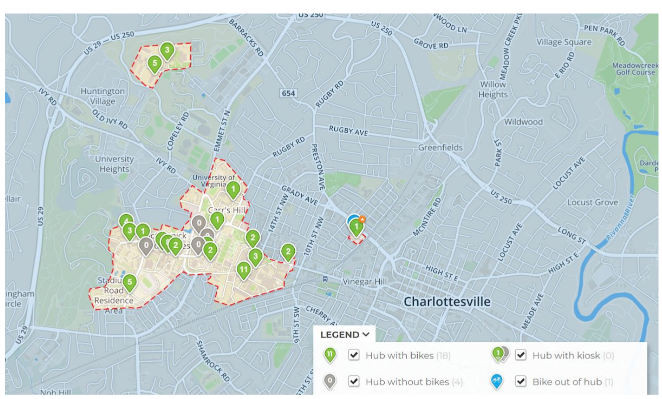


Figure 1.8: System Area of UBike

As can be seen, UBike services the vast majority of the University of Virginia campus, with an emphasis on areas such as Central Grounds, student residential areas, and the UVa hospital. However, its station-based nature limits it to the campus of the university. It should also be noted that UBikes themselves are powered by a solar power energy source for headlights and taillights, which both increase the sustainability of the bike. Furthermore, the UBike system is not restricted to UVa students or affiliates as community members and visitors are able to use UBikes. Pricing options include daily, monthly, biannual, and annual membership plans with discounts as an added incentive for UVa students, faculty, staff, and alumni (UBike, 2018).

Pedestrians

Periodically, the Virginia Statewide Bicycle and Pedestrian Count Network uses counting technology to record the number of times pedestrians walk on specific streets. While my group could not find information for the entire county, the network did focus on the city of Charlottesville, and has a number of tracking devices in areas ranging from Emmet Street to the Downtown Mall. According to the figure below, Emmet Street has a daily average of 538 pedestrians and the Belmont Bridge has a daily average of 199 passersby. Combining this information with the counts near McIntire Park and Charlottesville High School, there are roughly more than 1300 people in the city that rely on walking for at least part of their travels on a daily basis (Pedestrian Count Network, 2019). But it should be noted that this estimate does not take into account the large number of workers that reside near their local businesses or UVa students and grade level students that walk to and from school each day.

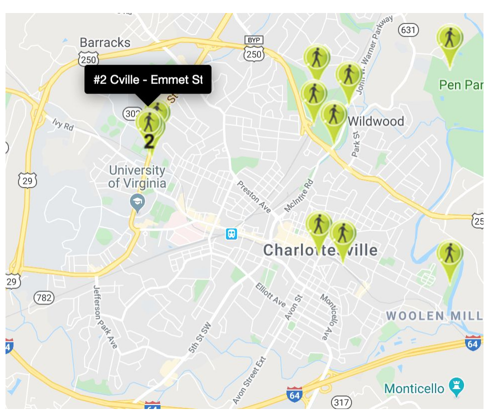


Figure 1.9: Charlottesville Pedestrians (Virginia Bicycle and Pedestrian Count Network)

My group also hopes to explore solutions that combine walking a shorter distance to access more personalized forms of transportation, such as a community rideshare service, that can bring the pedestrian to his or her final destination.

Mission Statement

We hope to promote sustainable transportation in the Albemarle/Charlottesville community while emphasizing renewable energy, efficiency, reliability, and accessibility.

Generation and Selection of a Requirements-Based Design Concept

Generate: Design Requirements

Product requirements

My group determined that a solution that befits the challenge space must be multimodal in that it addresses a variety of requirements specific to our challenge of improving transportation in Charlottesville and Albemarle County. In order to consider the life cycle and lasting impact of our solution, my group decided to focus on the following values that, together, would provide a strong foundation for the basis of our solution's implementation.

Requirement Values:

1. Sustainability

   We will focus on creating solutions that make transportation in the area more sustainable by transitioning to renewable energy as a major source for vehicles and reducing the use of fossil fuels to lower greenhouse gas emissions.

2. Efficiency

   We will work towards improving transportation efficiency by reducing the time needed for daily commuters working in Charlottesville.

3. Reliability

   Our solution will promote regular transportation that can offer stability regarding travel time and stop locations.

4. Accessibility

   We want to improve the current transportation system in a way that benefits the largest portion of the population possible. Accessibility is defined in terms of location and ability to reach residents of all ages within the county.

5. Affordability

   We want our solutions to be affordable for the city, county, and the residents of the affected areas.

6. Safety

   We will ensure that public transit will be safe for all residents and determine the local areas where individual means of travel such as walking or biking could be possible. This value applies to all stages of our solution including any materials or working conditions to create related products or processes.

Requirements, Metrics, Specifications (RMS) Combination Brainstorm:

Because our metrics and specifications are needed to fully describe our requirements, my group formed a combined table of all three aspects in order to brainstorm 17 possible options for consideration.

Table 1.3: RMS Table

Ranking Key:

- 1 – essential
- 2 – important
- 3 –would be nice to achieve

Qualitative Abbreviations:

- P – Performance-related
- F – Finance-related
- V – Values-based

Specifications Abbreviations:

- A – acceptable result
- I – ideal result

Requirement/Reason	Rank	Qualitative	Metric	Specifications
1. Our solution will reduce greenhouse gas emissions to achieve a more sustainable community	1	P, V	Percentage reduction compared to 2010	A:35% I: 45%[1] (IPCC goal by 2030)
2. Efficiency - Vehicle miles traveled (VMT) will be reduced	2	P	Percentage reduction of VMT	A: 25% I: 50%
3. Reliability - There will be no significant variance in daily pick-up times	2	P	Variation in daily pick-up times	A: ~5 minutes I: 0 minutes
4. Accessibility - All people in CHO/ALB will have easy access to some form of public transit	2	V	Percentage of residents with access	A: 75% I: 100%
5. Safety - My group will ensure that citizens have transportation available that is safe.	3	P, V	Number of violations to the Electronic Code of Federal Regulations	A: 0 I: 0
6. Affordability - My group will create a solution that is feasible and affordable for the city of Charlottesville.	1	F	Dollars available for transportation initiatives when compared to the CAT Paratransit Services General Fund Budget in 2019 of $3,750,750	A: ≤ $3,750,750 I: < $3,750,750
7. My group will ensure that any processes or materials needed to implement our transportation plan will have safe and fair working conditions for workers.	3	V	Number of injuries	A: 0 I: 0

[1] (IPCC, 2019)

8. My group will consider any new materials needed for implementation and assess their quality to ensure they are sustainable	3	V	Presence of energy seal to demonstrate energy efficiency certification	A: Present I: Present
9. Our transportation plan will be affordable to Charlottesville residents	1	F, V	Based on residents avg. income or based on current fares	A: ≤ $1.50/*way* I: *free*
10. Our transportation plan will be reliable for commuters	2	P	Margin of commuting length between days	A: < 20 minutes I: < 10 minutes
11. Our transportation plan will raise efficiency of current modes of transportation	1	P, V	Reduction of public transportation while still covering same routes	A: 10% I: 30%
12. Our transportation plan will be friendly to diverse groups of people	2	V	Usage rate of ramps etc. universal design elements (in % of routes)	A: 50% I: 100%
13. Our transportation plan will be sustainable in terms of nitrogen footprint	3	V	Reduction in nitrogen footprint compared to 2010 levels	A: 15% I: 25%
14. Our transportation plan will be safe for all age groups	3	V	Number of transportation related accidents per year	A: 100 (current number) I: 75 (25% reduction from current number)
15. Our transportation plan will optimize space on grounds to allow for other uses	3	V, P, E	Average percent of parking lots in use	A: 90% I: 60%
16. There will be no discrimination on the basis of wealth, race, etc. in the plan	2	V	Number of discriminatory incidents	A: 0 I: 0
17. Efficiency - Reduced traffic during rush hour	1	P	Percent traffic reduction	A: 25% I: 50%

From our full table, my group determined our five top RMS combinations that my group will later use to help assess the reasoning behind our multimodal solution.

Table 1.4: Top 5 requirements

Requirement #1	Reduce greenhouse gas emissions to achieve a sustainable community.
Requirement #2	We will create a solution that is feasible and affordable for the city of Charlottesville/Albemarle County.
Requirement #3	Raise efficiency of current modes of transportation.
Requirement #4	Our transportation plan will be affordable to Charlottesville residents.
Requirement #5	Reduce traffic flow in terms of personal vehicles

Our main goals center around a sustainable transportation system in Albemarle County, Virginia. The solution my group develops will be sustainable regarding its efficiency and ability to continuously meet the needs of current residents, but most importantly, with regard to energy use. Reducing greenhouse gas emissions from the transportation sector is essential to addressing climate change.

Breakdown of select RMS combos

In November of 2019, UVa and William and Mary partnered together to establish the shared goal of achieving carbon neutrality by 2030. Furthermore, UVa hopes to become 100% reliant on energy sources other than fossil fuels by 2050. It is possible that the University's improved sustainability plan is driven by the actions of Virginia State Governor Ralph Northam, who already "signed an executive order earlier this fall setting a goal for Virginia to produce 100% of its energy from carbon-free sources by 2050" (Kelly, 2019). Therefore, for Requirement #1, our solution will work towards the IPCC goal of reducing emissions by 45% by 2030, but my group will also be considering immediate changes that may be needed to meet UVa's new sustainability goals for 2030 and 2050. Because it may be hard to reach this goal at any individual mode of transport quickly, my group hopes that the combination of solutions developed will together reach the IPCC's target and help UVa achieve its own personal climate-related targets as well.

Table 1.5: RMS combinations that address sustainability

Metric	Specification
Percentage reduction compared to 2010[2]	A: 35% reduction I: 45% reduction
Year at which UVa achieves carbon neutrality 100% Fossil Fuel Free at UVa	A: 2035 I: 2030 A: 2060 I: 2050

The purpose of our second requirement is to ensure that our solution is affordable for the county of Albemarle and the city of Charlottesville. In order to obtain a baseline for standard funding and public transit pricing, my group found metrics in the Charlottesville city manager's proposed budget. It may be acceptable for new initiatives to require additional funding beyond the current budget, especially since the cost of carbon should be incorporated to more accurately reflect its impact. Below is Charlottesville's budget with regard to transportation services.

City of Charlottesville Budget

- CAT: $7,862,730
- Paratransit Services General Fund 2019 Budget: $3,750,750
- Other Funds 2019 Budget: $5,565,619
- Streets and Sidewalks/Street lighting Operations FY 19 Budget: $4,321,800
- Traffic Operations FY 19 Budget: $760,872
- Fleet Management Operations FY 19 Budget: $1,056,942

Table 1.6: RMS combinations to address funding

Metric	Specification
City of Charlottesville dollars available for transportation projects and initiatives[3]	A: > current budget dollars as long as additional funding sources are found

[2] (IPCC, 2019)
[3] ("City Manager's Proposed Budget: Infrastructure and Transportation", 2019).

	I: $0 needed outside of budget

Our fourth requirement focuses on affordability from the rider's perspective. In order to ensure that transportation is still affordable for Charlottesville residents, my group will use the standard bus fares for CAT and JAUNT as a baseline.

Table 1.7: RMS combinations to address affordability

Metric	Specification
Standard prices for Charlottesville Public Transit[4] ● Current CAT: 75 cents for one way or $1.50 unlimited per day ● Current JAUNT: $1.50 each way	A: Riders pay up to $0.25 more per trip for an initial period to help fund new initiatives I: Riders pay current price regardless of changes to vehicles or routes

Drivers of personal vehicles can also receive up to 58 cents per business mile driven by the federal government for tax reductions (IRS Release, 2019).

Generate: Solution Concepts

Team internal reflection

Based on our collection of individual reflections, my group developed a list of four main solutions that blended together our ideas. The final list below is followed by a more detailed description of each solution.

Table 1.8: Solutions

Solution #1	Bus system rerouting
Solution #2	Electric bus implementation
Solution #3	Marketing campaign for alternative forms of transit
Solution #4	Establishing sidewalks in areas needed/walking for schools

[4] (Charlottesville Area Transit Rider's Guide, 2019).

Route Alteration for Current Bus Routes

Routes could be changed to better serve riders in the area by reaching a larger number of people that currently use their personal vehicles for everyday commuting. This solution could especially be useful in areas of frequent high traffic congestion during rush hour such as along US 250.

Strengths:

- Increased number of riders to meet vehicle capacity
- Reduced traffic congestion as a result of increased use of mass transit
- Faster travel time for daily commuters

Weaknesses:

- Public transportation could be less convenient for some riders
- Bus stop waiting times could add to an individual's commute time

Questions:

- Which areas of congestion currently are not sufficiently covered by mass transportation?
- Which types of vehicles are most responsible for congestion in these areas?
- Where can bus stops be added to current routes to maximize efficiency?

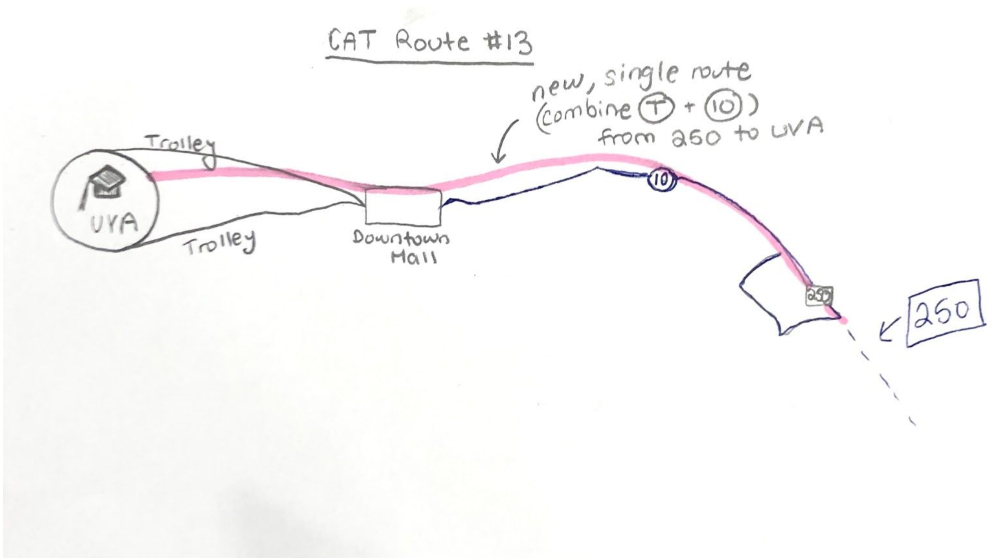


Figure 1.10: Potential New CAT Route

Transition to Electric Mass Transit in Charlottesville and Albemarle County

While my group especially hopes to help UVa switch to electric buses, this change can definitely be implemented at the city and county level. If CAT and JAUNT could make this transition along with UTS, the process may be easier. In addition, Charlottesville City Public Schools and Albemarle County Public Schools could implement electric buses.

Strengths:

- Would significantly reduce greenhouse gas emissions from transportation in the area
- Could establish a central location for charging all electric buses in the area
- Individual riders would not need to change daily travel habits
- Lower total cost of ownership and reduced maintenance costs leads to higher return

Weaknesses:

- Requires full support from all transportation authorities
- Would need to occur roughly within the same timeframe to ensure a smooth transition
- Higher upfront cost for the purchase of a new electric fleet

Questions:

- What pilot programs are available that can help the county begin the switch to electric?
- What sources of funding are currently available?

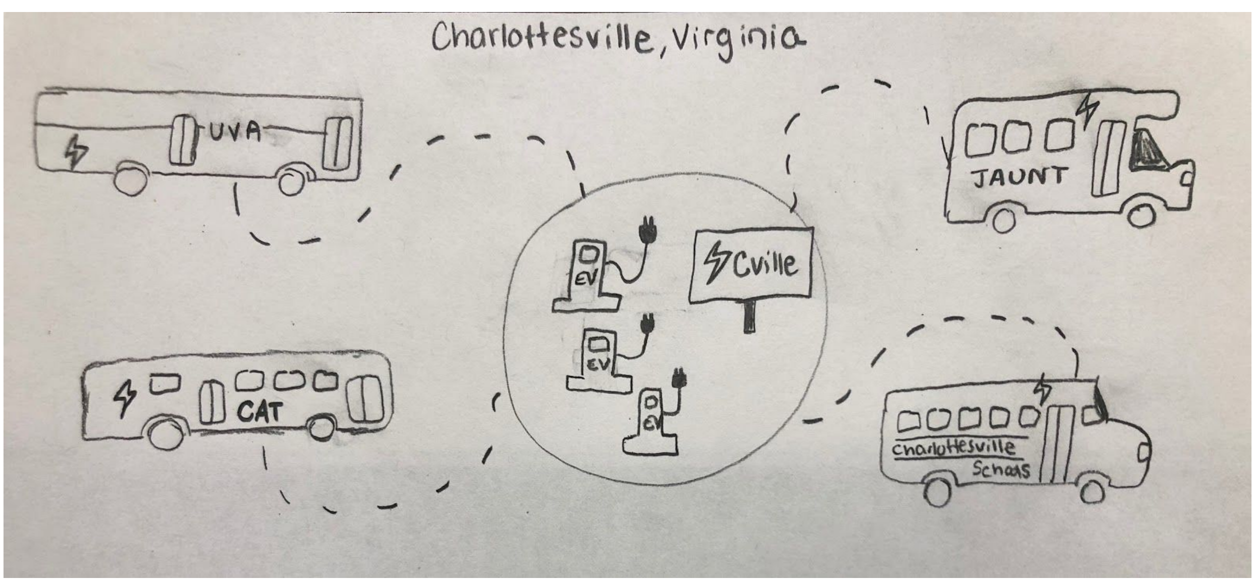


Figure 1.11: Organizations Benefiting from a Central Charging Center in Charlottesville

Marketing and Campaign for Alternative Forms of Transit/Travel

In this campaign, my group would promote modes of transportation that do not rely on fossil fuels. This campaign could initially target UVa staff since the majority of emissions from transportation at the university are from staff members. Then, it could expand to residents that frequently travel in downtown Charlottesville. Beginning at the University, staff members may face higher costs for reserved parking spaces, but could earn points for using alternative forms of travel such as riding the buses, biking, or walking to work. These points could be exchanged for a parking spot guaranteed on certain days or other rewards.

Strengths:

- Reduces total greenhouse gas emissions
- Encourages carpooling or other shared forms of transit
- Provides incentives for changes in commuting habits
- Joins the community together in addressing climate change

Weaknesses:

- Individuals would face higher upfront costs for individual parking spaces
- Drivers may search for cheaper parking options off Grounds

Questions:

- How could members benefit through additional rewards by relying on alternative forms of travel?
- How could the higher upfront cost in parking be used to benefit participants in return later in the process?

External Research

1. *Sources of Funding through Policy Change*

   First, my group must consider how part of the solution lies in obtaining necessary funding for any changes or improvements to the current transportation system in the county. Going forward, politics may play a crucial role as in 2016, "over $200 billion was at play through local and state ballot measures" regarding the approval of funding for transportation (Walker, 2016). Additional funding was granted to areas that voted "yes" on updated transit plans, amendments, and tax increases that went to improving transportation in the area. A few years ago, Fairfax County voted to approve obligation bonds that supported the repair of the Washington Metropolitan Area Transit system. Some cities, such as Atlanta, have taken major action by approving billions of dollars in taxes for public transit projects going forward (Walker, 2016).

Strengths:

- Demonstrates public support and consensus that transportation funding is needed
- Would directly cover the amount necessary to implement change in the city/county
- Would allow residents to have a voice in the direction of transportation in Charlottesville

Weaknesses:

- Long process
- Majority support needed for funding to be approved
- There could be resistance to an increase in taxes.

Questions:

- When will Albemarle County or Charlottesville attempt to pass new legislation regarding funding for transportation?
- What current projects still need more funding?
- What projects are already being planned for future years in the transportation sector?

2. *The Potential Role of Autonomous Vehicles: Autonomous Taxis*

Although still not common on the roads, autonomous vehicles may shape the future of transportation in the decades to come. In an interview, Professor Donna Chen, Assistant Professor of Engineering Systems and Environment at the University of Virginia, suggested that the transition, although unclear regarding the timeline, is present in future projections for transportation in Virginia. This fall, she attended a meeting in Charlottesville called “Autonomous Vehicles in Central Virginia: A Regional Conversation.”

Work is being done on autonomous vehicles to perfect mechanisms other than driving itself (Moriwaki, 2005). According to a recent U.S. Patent on autonomous vehicles, an important feature needed would be sound notifications for passengers to alert them of any information since a driver may not be present (Harper, 2019). In addition, designers are encouraging electric vehicles to be made with detachable or replaceable parts now that could change its “firmness of ride of the vehicle, braking performance/sensitivity, nominal suspension height, effective steering ratio, etc.” (Scaringe, 2019).

It has been predicted that autonomous vehicles could have an enormous impact on total energy use, and could “reduce energy use per vehicle by up to ~80% from platooning, efficient traffic flow and parking, safety-induced light-weighting, and automated ride-sharing” (Greenblatt, 2015). Through doing so, it would also significantly reduce greenhouse gas emissions.

The best way to first establish autonomous vehicles in society could be through taxis. According to a study on the impact of AV taxis in NYC, it was estimated that autonomous taxis would lower greenhouse gas emissions by 73% and overall energy consumption by 58% “compared with the fleet of the conventional internal combustion engine vehicles” (Zhang, 2019).

AV taxis could completely transform the current commuting habits of residents in Albemarle County. It would provide a number of benefits that would have a positive impact on the community. If this solution were to impact UVa, it could be implemented by targeting UVa staff members as potential customers. By taking taxis to and from work, staff can lower the University’s overall emissions from transportation.

Strengths:

- Lowers energy use per vehicle
- Lowers greenhouse gas emissions
- Extremely efficient
- Convenient

Weaknesses:

- Technology is still improving
- Users may be resistant at first because of safety concerns
- The cost of riding taxis is currently more expensive than owning a car

Questions:

- Should my group prepare for the commercialization of AV in the near future?
- How can my group reduce the cost of using taxis for everyday transportation in less populated cities such as Charlottesville?
- What local regulations currently prevent this solution from being implemented?

3. *Bus Rerouting*

In order to further investigate the commuting patterns in Charlottesville, my group used Google Maps to examine the average traffic flow during rush hour on both weekdays and weekend days. Based on the data, areas with the most regular traffic congestion center around the US 250 highway and the center of Charlottesville between UVa and the downtown mall.

4. *Bus Electrification at the University of Virginia*

The implementation of electric buses is a necessary step in reducing emissions and would have a lasting impact on the greater Charlottesville area. According to Brian Cameron, Marketing and Outreach Coordinator for UVa Parking and Transportation, the University understands that it ultimately will switch to electric buses in the future. Through his research of the fleet of 27 UTS buses currently operating at the University, Cameron predicts that electric buses may be most easily initiated on shorter routes such as the Redline or Northline Express. With only 6 to 11 loops in total per day and a long period of rest between cycles, UVa would not have to worry about longer charging times for the buses and could also gain crucial feedback from piloting for these less relied upon routes (Cameron, 2019). In fall of 2019, UVa held a meeting with Proterra but is also considering working with the bus manufacturer, New Flyer.

Strengths:

- A new fleet of electric buses could also allow for possible rerouting as well to make the UTS system more efficient
- Would enable UVa Parking and Transportation (P&T) or the city of Charlottesville to create a center for EV charging that could be used for multiple types of electric vehicles
- Would not change commuting habits for those that already rely on public transit

- Could reduce UVa staff transportation emissions

Weaknesses:

- The University still needs outside funding for project
- New P&T facility will determine a timeline of the implementation depending on how prepared it is for managing and charging electric vehicles

Questions:

- How can my group ensure that the next UVa purchased fleet (or at least partial fleet) is electric?
- Will Blacksburg's decision to use New Flyer buses impact UVa's decision when determining the University's next bus company?
- How can the implementation of electric buses provide an incentive for UVa staff to ride the bus instead of driving individual vehicles to work? Could there be a rewards program since the buses are both more efficient and rely on clean energy?

5. *Bus Electrification for Albemarle County Public Schools*

Virginia is already on board for the transition to electric buses in public schools. In September 2019, Governor Northam announced that the Volkswagen Environmental Mitigation Trust (VW Trust) would provide the state with $20 million to begin implementing electric buses in the public school systems (Northam, 2019). Not only would this help fund the upfront cost of the buses themselves, but it would also help cover the costs of new infrastructure needed for charging stations.

According to Secretary of Natural Resources Matthew J. Strickler, "transportation pollution is the largest source of greenhouse gas emissions in Virginia." Helping the public schools begin this transition would have a major contribution to addressing the IPCC targets and reducing emissions. Just by replacing 75 current school buses with electric buses could reduce greenhouse gas emissions by 36 million pounds (Northam, 2019). By 2021, the state will work with Dominion Energy to have at least 50 electric school buses in operation (Natanson, 2019).

Strengths:

- Would promote the transition to renewable energy at all levels of the county
- Would set electric transit as a precedent for future generations taking the bus to school
- Funding through the VW Trust is available and can be applied for this year

Weaknesses:

- Higher upfront costs as expected

Questions:

- Applications for this grant are supposed to open early next year. How can Albemarle County Public Schools apply for this funding?
- What additional steps is the county currently taking to consider charging infrastructure for local school buses for when they do switch to electric?

Select: Key metrics and a promising solution

Through ongoing team discussion, my group ultimately determined that my group would narrow our focus on solutions that specifically could improve transportation mainly through the Charlottesville public schools and the University of Virginia. At the University of Virginia, my group hopes to help reduce staff emissions and total transportation emissions overall.

A concept classification tree: A summary of ideas

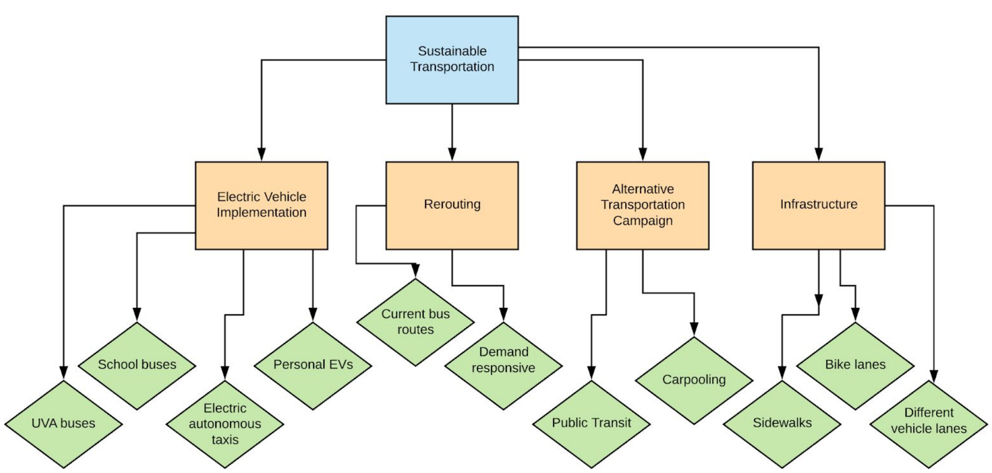


Figure 1.12: Concept Classification Tree for Decision-Making

After establishing the concept classification tree with 11 distinct ideas and determining our final goals, it appears that some of the branches under infrastructure such as bike lanes and different vehicle lanes can be removed. As of now, it would be difficult to determine the exact measurement of the reduction in greenhouse gas emissions as a result of these solutions, and so for this reason my group will continue to consider other options. We can also remove carpooling as a solution since the city is already making efforts to encourage carpooling such as UVa's CavPool program. For our multimodal solution, my group will focus on ideas that have not already been implemented in the county or Charlottesville community.

A decision matrix: Key metrics vs. best solution concepts

Using Table 1.8, a decision matrix was created to quantitatively determine the best solution.

Table 1.9: Decision matrix

	Requirement #1	Requirement #2	Requirement #3	Requirement #4	Requirement #5	Total Score
Requirement Weight	0.2	0.2	0.2	0.2	0.2	1
Solution #1						
Ability to Deliver	5	6	9	8	6	
Weight * Ability	1	1.2	1.8	1.6	1.2	**6.8**
Solution #2						
Ability to Deliver	10	6	7	9	5	
Weight * Ability	2	1.2	1.4	1.8	1	**7.4**
Solution #3						
Ability to Deliver	5	6	9	8	10	
Weight * Ability	1	1.2	1.8	1.6	2	**7.6**
Solution #4						
Ability to Deliver	5	4	5	10	6	
Weight * Ability	1	0.8	1	2	1.2	**6**

A decision matrix was used to assess our four solution ideas using the five requirements in Table 1.4 in order to quantitatively determine which of the solution options would be the most viable. My group considered a diverse set of potential solutions ranging from electric vehicle implementation to changes in routing and infrastructure. Our requirements included decreased emissions, affordability to authorities, efficiency, affordability to populace, and reduced traffic flow. The aforementioned five requirements were weighted equally during the selection process to prioritize a solution that would not only benefit the environment but also be financially feasible for the government and the people. Together, these requirements provide our informed perspective on what needs to be considered when making changes in the current transportation system .

Confirming the selection

Based on the decision matrix, it appears that the second and third solution ideas should definitely form the framework of our multimodal solution. According to the matrix, our third solution of developing a marketing campaign for alternative forms of transit is most viable. This makes sense because of its relatively low cost and high ability to deliver, especially with regard to the fifth requirement of reducing the number of total vehicles and improving traffic congestion. Furthermore, this solution does not require an advanced skill set that may be required for transit rerouting. Our second solution of implementing electric buses is also an achievable goal. While my group should continue to gain more knowledge on the implementation of electric buses in other cities and nations, we can still work towards acting on this solution by researching additional funding options and long-run savings. The first solution for bus rerouting is also possible according to our weighted values. More external research is likely needed, but it is clear that rerouting mass transit would be most beneficial between UVa and the downtown mall and along US 250.

Summary of the selected concept

Our multimodal solution will work to reduce Albemarle emissions by 45% (compared to 2010 levels) by 2030, address emissions from UVa Staff, and overall, help UVa reach its new goals of carbon neutrality by 2030 and 100% fossil fuel free by 2050. The solution pieces may be completed simultaneously, or, to ease the transition, could be implemented in the following order:

1. *Marketing Campaign for Alternative Forms of Transit*

   First, UVa, Charlottesville, and Albemarle County could work together to launch a major green transportation campaign that would encourage commuters to adapt their current everyday traveling habits. Sustainable changes could consist of the following:

   - Purchasing personal electric vehicles
   - Walking or biking to school or work
   - Relying more on Mass Transit as a main form of transportation

   This campaign can take place between the time electric fleets have been ordered and their arrival to maximize efficiency during the time when the city or county does not yet have access to electric mass transit. During this brief intermediate stage, my group can ensure that fossil fuel emissions still decrease even without the change in vehicles on the road.

2. *Electric Bus Implementation Across Albemarle County*

   Next, electric bus fleets should be implemented within the county, city, and University. Based on the current status of progress and available funding, this transformation could take place in the following order:

   - Charlottesville central vehicle charging center
   - University of Virginia UTS system
   - Albemarle County Public Schools
   - CAT
   - JAUNT

3. *Bus Rerouting in Areas of High Traffic Congestion*

Lastly, with a new fleet of electric buses for the school system, the university, and later the city and county, transit authorities can adjust routes to maximize traffic flow in the following areas:

- University of Virginia
- Downtown Mall
- US 250 Bypass

Transition between projects

The previous sections provide an overview of the transportation challenge space and a solution outline that will likely be helpful for groups that take up this project in the future. The second project that deals with hospital-acquired infections begins with the next section and henceforth, the team being referenced is the group that I joined in the Spring 2020 semester. Prior to my joining, this new group had completed the previous sections with respect to hospital-acquired infections, namely, an overview of the challenge space and an outline of what was thought to be the best solution. The solution concept that this group had decided upon was a device that used ultraviolet C (UVC) radiation to irradiate bacteria that gathered at the bottommost area of a sink U-bend with the intention of impeding their ability to travel up the drain. The remainder of this paper documents our attempt to construct a prototype and carry out testing to gauge the feasibility and effectiveness of said device.

Exploration of a design concept

Prototyping

Overview

Having identified a most promising solution concept, our team now seeks to confirm the ability of our concept to satisfy key design requirements. The team intends to explore the true promise of the concept by developing a physical prototype of the solution and using it as the basis for a set of experiments. The experiments are intended to explore the actual ability of the solution concept to address the problem of hospital acquired infections. Following experimentation, results will be analyzed, and the team will recommend future project directions. The team will either present a more detailed engineering description of the design (if the experimental results show promise), or they will present ideas for a revised design that the experiments suggest could be more effective.

Specifically, the primary goal of establishing the physical prototype was to determine the effectiveness and feasibility of using ultraviolet C (UVC) radiation to kill bacteria when filtered through quartz glass in the constructed sink-trap system. Producing an exact physical representation of the sink-trap system will allow us to determine the practicality of using UVC radiation to prevent hospital acquired infections arising from sink wastewater that could spread to patients, a group of people who are already at risk.

STEM basis for work

Colony counting

Counting bacterial colonies is the main method of data collection for this experiment. Counting colony-forming units (CFUs), a unit that estimates the number of viable cells of microorganism in a sample, requires bacterial culture. Bacterial culture broadly refers to letting bacteria reproduce in a predetermined culture medium (agar in our case) under the standard controlled laboratory conditions that will be specified in the procedure. This microbiological technique is especially important because it is by far the simplest and most accessible method by which we can determine the abundance of bacteria in the sink system, specifically the number of viable organisms. If the number of colonies was too high to count, then only a fraction (typically a quarter or a sixteenth) of the dish will be examined. If available to us, a click counter and pen will be used to enumerate colony-forming units.

Image processing

If the colonies themselves were too small to count by hand, then there exists software solutions for this problem. ImageJ is a image processing program that has the capability to semi-automatically or automatically count the number of objects greater than a certain size and belonging to a certain shape in a frame of view and specifying the scale beforehand allows us to use this program to not only determine the number but also the size of CFUs. Software such as ImageJ minimizes any human error that may arise from counting by hand.

Ultraviolet germicidal irradiation (UVGI)

This experiment depends solely on the efficacy of ultraviolet germicidal irradiation (UVGI). At its core, this method uses short-wavelength ultraviolet radiation (UVC) to either kill or inactivate microorganisms. This is done by destroying nucleic acids and disrupting their DNA, which contains genetic information, and this leaves them unable to perform vital cellular functions. In most cases, the DNA of the affected organism is denatured due to the formation of pyrimidine dimers. Pyrimidines refer to one of the two types of nucleobases in DNA and include cytosine (C) and thymine (T). Such dimers can be seen in the graphic below.

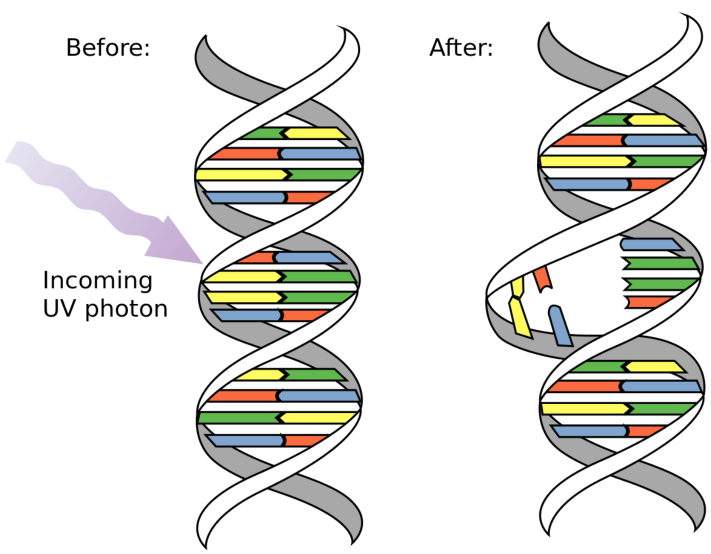


Figure 2.1: Damage to DNA from Ultraviolet Radiation (Retrieved from public domain)

In the above image, two adjacent bases bind to each other instead of binding across the ladder and this is what specifically disrupts DNA replication (US Army, 2011).

Optics

This project is highly dependent on the electromagnetic radiation's transmission in order to function. The first portion of the experimental procedure is necessary to determine if the lab is conducted with the correct wattage and that the quartz glass is capable of transmitting the proper amount of UV-radiation to sterilize the section that it hits. For the light transmittance we plan to use a UV-C emitting light. UV-C was chosen because it has germicidal properties, however, it has a wavelength between 200 and 280 nm, which is blocked by most glasses. Quartz glass, however, is often used in spectroscopy because it allows for UV light to pass through unhindered. A rough graph of various cuvette transmittance spectra is pictured below. As depicted, glass and acrylic plastics are unable to be used for our experiments because they are unable to allow enough of the germicidal UV-C light to pass through the lense.

Table 2.1: Transmission Wavelengths of Various Materials

Material	Transmission
Optical Glass	340 - 2,500 nm
UV Quartz	190 - 2,500 nm
IR Quartz	220 - 3,500 nm
Sapphire	250 - 5,000 nm

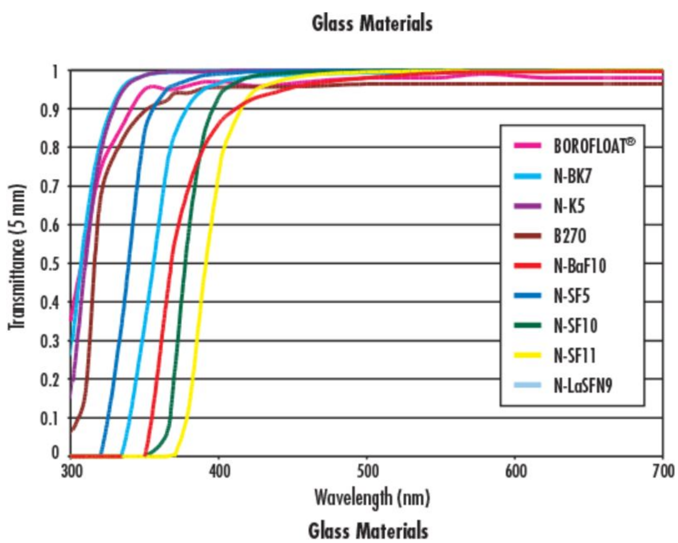
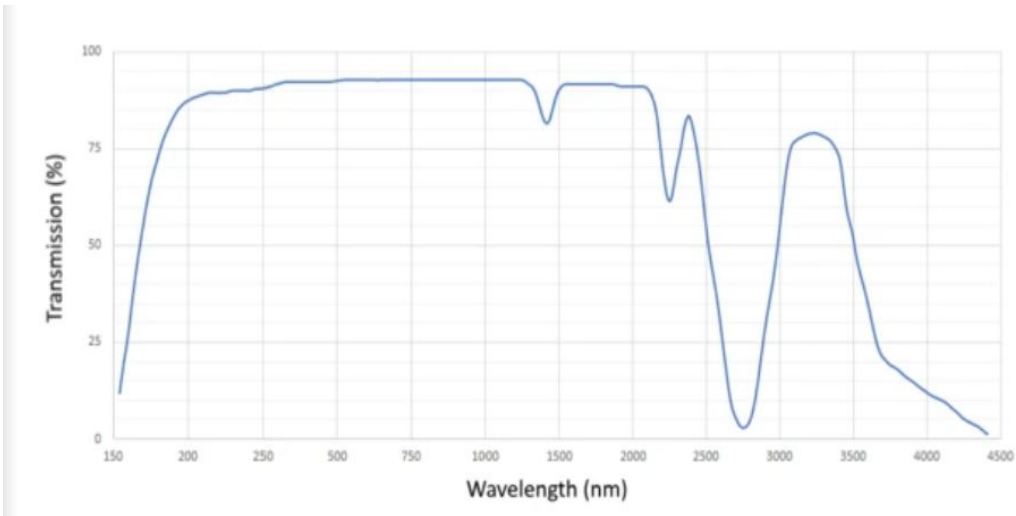


Figure 2.2: Transmission Wavelengths of Various Materials (Retrieved from https://www.edmundoptics.com/knowledge-center/application-notes/optics/optical-glass/)

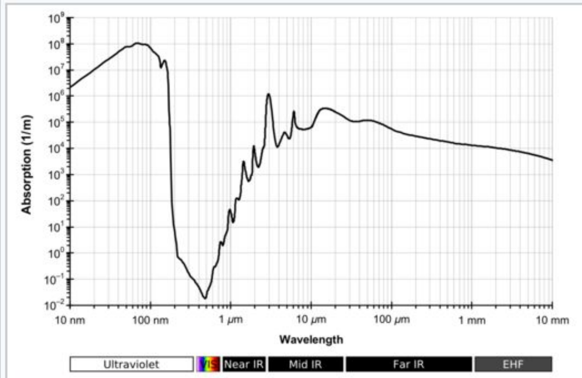
As pictured above, a vast majority of commercially available glass optic materials only transmit effectively above 350 nm. This poses a significant problem because UV-C has a wavelength between 200 and 280 nm which means that the device will not be able to use standard glass lenses to transmit the germicidal light to the U-bend. A solution to this issue is the use of quartz optical glass. Pictured below is the transmission graph of a quartz cuvette.



Transmission through UV quartz glass between 150 nm and 4500 nm.

Figure 2.3: UV Quartz Glass Transmission Spectrum

As shown above quartz transmits over 80% of all light making it ideal for the use of our lense into the U-bend. Accounting for this slight loss of 15-20% of the germicidal rays still allows us to effectively expose the bacteria to the UV-C light. Another important point to consider is that standard absorbance/transmittance measurements are calculated with 1 cm thick material, indicating that less will be absorbed provided we used a thinner pane of quartz glass. A second key portion to consider is the absorbance of water, water has a unique absorption spectrum as shown below.



Liquid water absorption spectrum across a wide wavelength range

Figure 2.4: Liquid Water Absorption Spectrum

(Retrieved from https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water)

However, UV-C light that is closer to 280 nm transmits quite well. The success of the UV-C light as a sterilization method is seen in water purifiers for backpacking that utilize UV-C light.

Statistical concepts used for data development

Performing statistical analysis on the numbers of CFUs can ease data interpretation. Descriptive statistics will most certainly be performed to determine measures of central tendency, range, and spread of the data set as these values are essential to any experiment. Inferential statistics may also be useful in that it allows us to still make conclusions from data that may have been subject to random variation. Such variation may include sampling variation due to the inability to count all CFUs or observation error due to misidentifying a CFU. Basic statistical hypothesis testing techniques such as Student's *t*-test may prove useful.

Prototyping summary

The physical prototyping was split into two main stages: the manufacture/assembly of the physical prototype and two the testing of the physical prototype. The manufacture and assembly can be completed without the usage of highly specialized equipment as all necessary parts can be purchased, 3D printed, or borrowed from the university. Details of the manufacture/assembly and purchase components are listed below. As stated above, effectiveness will be measured by the percent elimination of bacteria using the cell culture methods that will be detailed in the following sections.

Supply List and Explanation

Table 2.2: Supplies

Parts	**Source/Best Place to Buy**
Sink Basin	Commercially Available from Hardware Stores (Can be Obtained at Home Depot or Lowes)
U-bend Connector	Commercially Available from Hardware Stores
UV-C Light	Baiwei Lighting ASIN: B07YCM12XV
Quartz Glass	Alpha Nanotech Inc. Part No. QPX0015X8A19
Teflon Tape	Commercially Available from Hardware Stores
Pipe Connectors	Commercially Available from Hardware Stores
Box/Cover	Commercially Available from Hardware Stores
Socket + Power Chord	Commercially Available from Hardware Stores
Pipe Cutter	Commercially Available from Hardware Stores
Electric Hacksaw	Commercially Available from Hardware Stores
Glass Cutter	Commercially Available from Hardware Stores
Waterproof Sealant/Adhesive	Commercially Available from Hardware Stores
Escherichia coli (*E. coli)* K-12 Strain	Carolina Biological Item # 155068
Bacillus subtilis (B. subtilis)	Carolina Biological Item # 154921
Liquid Culture Vials	Carolina Biological Item # 715060
Petri Dishes	Carolina Biological Item # 740996
Agar Solution Supplies	Carolina Biological Item # 821045

Gram Staining Supplies	Carolina Biological Item # 319570
Personal Protective Equipment (Gloves, Goggles, & Coat)	Borrowed from University or Purchased at University Bookstore
Cleaning Supplies (Bleach)	Borrowed from University

Select part descriptions:

- The first optional piece for this experiment is a sink basin, which will provide an additional level of structure to enable the device to more accurately represent the device how it is intended to be used. This piece is not completely necessary for testing, but provides a better image of how the device works in a system.
- The base for this device is the U-Bend connector, which provides the underlying structure of the device. A plastic PVC pipe is preferred due to the ease that it can be modified and cut.

Figure 2.5: PVC Pipe

- UV-C lights; the UV-C light provides the electromagnetic radiation that is necessary to kill bacteria. The device will be built around the UV-C light and will allow for the light to pass through the window cut into the pipe. The picture represents a form of UV-C light in order to provide a visual representation.

Figure 2.6: UV-C Emitting Light

- Quartz glass: This will provide the opening that allows for the UV-C light to pass into the U-bend and will be fixed into the plastic structure of the PVC pipe. For this to function the glass needs to be a thin pane and small enough to be embedded into the pipe.

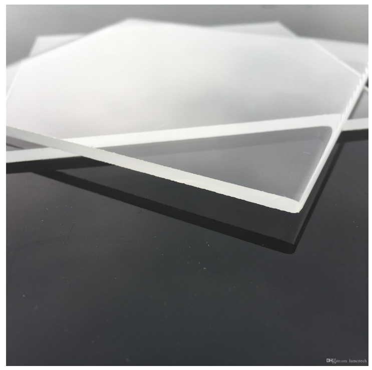


Figure 2.7: Quartz Glass Pane

- For this structure a sealant is required in order to fix the glass to the structure and seal the box that guards against UV light emission. For the testing portion, Teflon tape is optimal until we can create a more permanent fixture.
- Connectors for pipes are also required in order to integrate our structure into the sink itself and refasten a new U-bend.
- Another important material that is needed is a black box or cover to seal the outside from harmful UV-C rays. For the proof of concept, we will utilize opaque plastic sheets and teflon tape to create a sealed structure.

Tool descriptions:

- A pipe cutter is greatly helpful in the construction of the device, it allows for clean cuts of the pipe and allows for effective modification regardless of the pipe's material.
- An electric hacksaw is also necessary to provide the ability to make clean cuts in the metal and to allow for the ability to create a hole for the quartz glass to be placed in.
- A glass cutter is also essential to cut the glass to a precise shape in order to ensure a proper fit.

- A flexible waterproof adhesive is necessary to construct the model and ensure that the pipe remains sealed and the device remains fixed.

Bacterial culture materials:

- The K-12 strain of *E. coli* is non-pathogenic and representative of Gram-negative bacteria
- *B. subtilis* is also non-pathogenic and will be used to represent the Gram-positive bacteria
- Vials are needed to grow the liquid cultures.
- Petri dishes are also necessary to grow the solid cultures of bacteria to test the success of the sterilization process
- Also important are supplies needed for Gram staining
    - Crystal violet is necessary for the initial colorization step in Gram staining; it accounts for the Gram-positive bacteria's distinctive purple color.
    - Safranin is necessary for the final step of the Gram staining process and gives Gram-negative bacteria the distinctive pink coloration.
    - Iodine is necessary in the Gram staining process in order to fix the crystal violet dye in the Gram-positive bacteria to prevent the decolorization by the acetone.
    - Acetone is necessary to decolorize the Gram-negative bacteria and wash off the crystal violet dye, this allows for the clear differentiation between the Gram-negative and Gram-positive bacteria.
    - Slides are used to observe the bacteria under the microscope and assess the bacteria cultured.
    - A microscope is necessary for the examination of the slides.
- An incubation chamber is necessary in order to grow the bacteria.
- Sanitization equipment is necessary to clean up lab spaces.
    - Bleach solution can be utilized to sterilize surfaces.

Personal protective equipment:

- Nitrile/latex gloves
- Eye protection - goggles

- Lab coat for splash protection

Safety & Lab Space Approval

Prior to starting this project, the team underwent biosafety training. The agents with which we worked are considered biosafety level-1 (BSL-1) materials (US Dept of Health, 2009). Before working with any BSL-1 biological materials, each group member had to complete a basic biosafety online training module that was administered by UVa Environmental Health & Safety. This module can be found at https://ehs.virginia.edu/Biosafety-Training.html and stressed concepts such as proper and improper lab practices and discussed the decontamination of potentially infectious materials before disposal using bleach or isopropanol. Personal protective equipment (PPE) is relaxed at this level as the only required labwear was goggles, nitrile gloves, and lab coats. After this training was completed, our capstone advisor submitted our project proposal to the UVa Institutional Biosafety Committee (IBC). The IBC does not reject BSL-1 projects but did provide recommendations and asked for clarifications about aspects of our experiment. Our capstone advisor also helped us secure an isolated space in which we could construct our prototype and conduct experiments. This space was on the ground floor of Thornton A-Hall.

Experiments

Specific experimental procedure description

Our physical prototyping procedure was built around two parts. The first main part was to ensure that the light effectively functions at killing bacteria both alone and when filtered through the quartz glass. The second major test is determining how well it functions in the completed system where we test its effectiveness in the enclosed system.

Procedure Part I Initial Test - Solid Cultures Proof of Concept

1. Obtain Petri dishes and prepare an agar solution to provide nutrients for the bacteria.
2. Inoculate 3 dishes with the *E. coli*, and 3 dishes with *B. subtilis*
3. Divide into 3 groups with one of each type of bacteria Petri dish control, UVC-radiated, and UVC-radiated with quartz glass

    a. Leave the control group alone, allow it to grow in the incubator unhindered. This is necessary to compare initial growth
    b. Expose the second group to UVC radiation for 25 minutes
        i. To accomplish this, leave the top open in the Petri dish and conduct radiation procedure with safety goggles on and in a designated space to avoid eye and skin damage
    c. Repeat part b with a pane of quartz glass in-between the light and the Petri dish
4. Allow for growth in the incubation chamber for 48 hours at 35 degrees Celsius
5. Compare and assess the growth of each of the Petri dishes with a Gram staining process
    a. Note: *E. coli* is Gram-negative and *B. subtilis* is Gram-positive

Notes: This procedure is designed to test the effectiveness of the UVC light in preventing the growth of bacteria. Though this test is to measure the effectiveness of the set-up, it is a proof of concept, simply to determine that the idea is viable and works in practice. There is three separate classifications for each bacteria; the control is so we have something to compare our results to, there is one that works with the just the germicidal UV-C light, and the third one has both the quartz glass and the UV-C light so that we can determine if the quartz glass has an adverse effect on growth. This procedure requires an incubator that can be set to 35 degrees because that will allow both *E. coli* and *B. subtilis* to grow simultaneously in the incubator. Though it is not necessary to grow them both in the same incubator, it significantly reduces the gear requirements to conduct the experiments as incubators are expensive. From this experiment, we will be able to determine how effective the light was based on the growth amounts of the bacteria. In order to ensure that reliable results are recorded, we can conduct this experiment multiple times and multiple samples can be taken from each Petri dish. This will allow us to conduct a statistical analysis on the samples to determine how successful the sterilization procedure was.

Gram staining

The Gram staining procedure is a standardized process that is included below. The rationale behind different steps is explained beneath the process, and the explanation of the materials used is indicated in the supply section.

Module: **The Gram Stain**

<u>Procedure</u> - click "start lab"

From a liquid culture, take a loopful of bacteria emulsify it in a small drop of water or saline on the slide. This should be a thin, not milky, suspension or it will not stain properly. Air dry the slide. *This is done automatically in the virtual module.*

To begin:

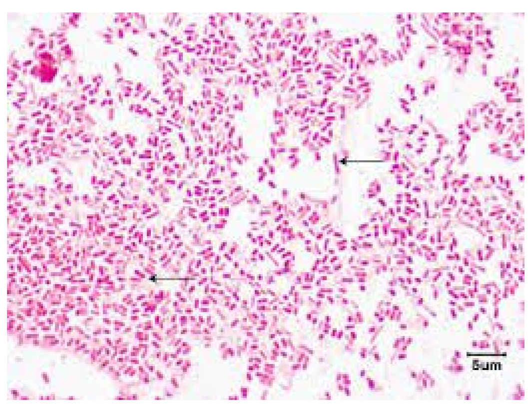
1. Heat fix the slide: click on the Bunsen burner, pass the slide gently two or three times (1-2 seconds) through the flame. Do <u>not</u> overheat - this will cause distortion of the cells.
2. Flood the slide with crystal violet for 1 minute
3. Rinse with H_20
4. Flood the slide with iodine for 1 minute
5. Rinse with H_20
6. Decolorize with alcohol for 5-10 seconds
7. Rinse with H_20
8. Flood the slide with safranin for 1 minute
9. Rinse with H_20
10. View slide under the microscope

The "slide" contains *E. coli* and *Staph. aureus* – is that what you see?
If not, think about what you might have done incorrectly
Then, repeat the exercise.

When you are finished with the exercise, click on "Examine Examples" to see actual micrographs of several bacteria that have been gram stained. You will recognize the names of many of the bacteria from lecture.

<u>Some Pitfalls:</u>

1. Slide not heat-fixed: smear will wash off → what would you expect to see?
2. Slide over heat-fixed: cellular morphology may be distorted
3. Slide over-decolorized: gram-positive bacteria will appear gram-negative
4. Slide under-decolorized: gram-negative bacteria will appear gram-positive
5. Smear too thick: cells in very thick areas will not decolorize properly and gram negative bacteria will appear gram-positive
6. Insufficient time for safranin counterstain: gram-negative bacteria may be very faint and difficult to see



<u>Figure 2.8: Expected Results for Gram staining *E. coli*</u> (Retrieved from http://faculty.ccbcmd.edu/courses/bio141/labmanua/lab1/gnrod.html)

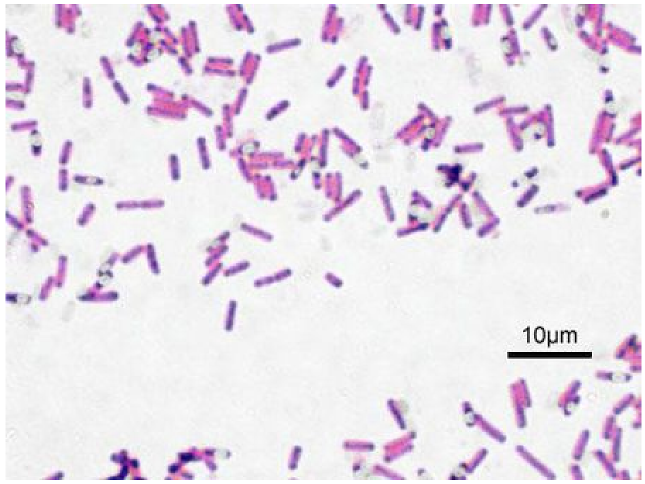


Figure 2.9: Expected Results for Gram staining *B. subtilis* (Retrieved from http://soft-matter.seas.harvard.edu/index.php/Bacillus_subtilis_spreads_by_surfing_on_waves_of_surfactant)

The above procedure was obtained from Michigan State University's Gram staining module (Gram Staining, n.d.). Gram staining is a standardized procedure that was developed in 1884 by Hans Christian Gram to make bacteria more visible and is capable of differentiating between different cell walls of bacteria classifying them into Gram-positive bacteria and Gram-negative bacteria (National Institute of Health, 2019). According to the National Institute of Health, Gram-negative bacteria are characterized by a thick peptidoglycan cell wall while Gram-negative bacteria have an outer membrane with a thinner peptidoglycan layer underneath the outer membrane. This structure allows for Gram-negative bacteria to absorb the crystal violet and maintain a purple color, this color is fixed with the iodine treatment which prevents its decolorization. The exterior of Gram-negative bacteria also turns purple with the crystal violet, but the iodine does not fix the color in the exterior membrane and it subsequently loses the purple coloration with the decolorization. The Gram-negative bacteria takes in the safranin dye and turns a pinkish color. This process will allow us to easily see the bacteria under a microscope and will enable us to see if there is any cross contamination between samples as *B. subtilis* is Gram-positive and *E. coli* is Gram-negative. The purpose of conducting a Gram stain is to help visualize the bacteria grown and to double check that no cross contamination occurred.

Specific Computational Description

The goal of the computational simulation procedure is to convert the tests conducted into a quantitative analysis. The initial procedure is proof of concept, and is simply there for a qualitative yes or no answer; however, in order to convert it to a more careful analysis, there are several steps to take. This provides the method for analyzing bacterial growth, and provides instructions for how to best analyze and visualize the data.

1. Conduct this test 3 times, to allow for a calculation of the accuracy of our prediction.
2. Within the Petri dish, count the number of colonies to compare each sample.
    a. Note it is important to use the same inoculation pattern for each sample in order to get a an accurate comparison
    b. This method allows for us to count many data points without growing a large number of samples.
    c. To accurately count the number of bacteria set up a grid system and count the number of colonies per block
3. Once this is complete create a scatterplot for the aggregate number of colonies for each method.
4. To compare the amount for each method conduct a linear regression analysis for time in UV light vs. number of colonies
    a. There should be 6 separate graphs
        i. Two per bacteria for the first procedure, one set accounting for no quartz glass and another set for the experiment with quartz glass
        ii. There should be one graph for each type of bacteria for the second procedure, that correlates radiation time to the number of colonies counted on the Petri dish.
5. From the analysis calculate the effectiveness of the device at reducing the amount of bacteria after use.
    a. From this data one should be able to determine the optimum amount of time that the UV-C light should run, or even if it is a viable solution

6. Further, the experiment can be repeated multiple times to generate an empirical distribution of bacteria colony data from the methods of experimentation. These data points provided by the outcome of the experiment allow for more robust statistical modeling and testing including tests of significance and creating summary.

Note: This procedure is designed to measure the effectiveness of the device in a more realistic setting. This design uses functions by first growing both the *E coli* and the *B. subtilis* bacteria in a liquid culture. Each liquid culture will then be mixed with water and allowed to sit in the U-bend device we created in order to allow the UV-light to sterilize the pipe while the UV light is turned on for 25 minutes. The solution will then have a sample taken from which will then be inoculated into a Petri dish filled with the agar solution. Similar to the first procedure the sample will then be allowed to incubate for 48 hours at 35 degrees celcius to analyze the effectiveness of the sterilization procedure. This process can be repeated with the light set at different amounts of time to analyze how much time is necessary for the sterilization process. Statistical analysis can be best conducted using statistical packages within SAS or MATLAB that are both capable of forming accurate and customizable graphs for our data.

Procedure for official U-bend Effectiveness Test

(Adapted from Kotay et al.)

1. A U-bend connector made of polyvinyl chloride (PVC) with the specifications specified in the supply list above will be purchased
   a. If the dimensions are later deemed unsatisfactory (too large), then a pipe cutter will be used to modify them
   b. If the pipe size cannot be physically modified, then larger or smaller connectors will be purchased accordingly
2. UV-C bulbs will be purchased and fixed at the bottommost point of the U-bend
3. Quartz glass according to the specifications above will be fixed into the plastic structure of the PVC pipe to provide the opening that allows for the UV-C light to pass into the U-bend

4. The P-trap system will be constructed by attaching corresponding pipes to the U-bend connector and a drainage source will be established to be used as necessary
5. All potential leaks will be sealed using Teflon tape as a sealant
6. The system will be sterilized using bleach to prevent contamination from outside sources immediately before the bacteria is introduced to the system
7. A cover will be oriented such that the outside of the system is sealed from harmful UV-C rays
8. A non-pathogenic strain of the bacteria, *E. coli,* will be grown in vials and incubated in parallel to the previous steps
9. A single isolated colony of *E. coli* will be inoculated in a 5 ml tryptic soy broth (TSB) that will be created following the instructions in the Bacteriological Analytical Manual (Center for Food Safety and Applied Nutrition, 2017)
10. To establish the *E. coli* in the sink P-trap, fill the P-trap with a solution of100 ml x 0.1 TSB and inoculated at a density of 10^3 CFU/ml
11. After inoculation, both ends of the P-traps will be covered with perforated Parafilm and be incubated at room temperature for 14 days to facilitate sufficient growth
12. After the P-trap was installed, 25 ml of TSB followed by 25 ml of saline solution will be added in a 1:3 ratio to mimic the nutrient exposure in a hospital
13. The medium in the P-trap must be replaced with fresh 0.1 x TSB every 48 h
14. An aliquot of medium and a swab sample from the inner surface of the P-trap will be plated on tryptic soy agar plates to monitor the growth of *E. coli* in the P-traps
15. The plates will be incubated overnight at 37°C, and CFU will be enumerated either by hand or using ImageJ as the situation requires
16. The culturing of *E. coli* will take place in a room separate from the sink gallery to avoid contamination.
17. The inside of the trap that is closer to the input will be swabbed to see if a biofilm containing the E. coli has extended upward

a. This will be done by drilling sampling ports along the length of the P-trap and fitting them with silicone stoppers
b. Sterile cotton swabs that are pre soaked in saline will be inserted through these sampling ports, and samples were collected by turning the swab in a circular motion on the inner surface
c. Sample swabs will be “pulse-vortexed in 3 ml saline, and serial dilutions were plated”

18. If the p-trap system used in the first experiment is reusable, then it will also be sterilized for use with the second bacteria, *B. subtilis*
    a. If it is not, then an exact copy of the system will be created
19. Steps 7-16 will be repeated with *B. subtilis*
20. All materials and agents used in this experiment will be disposed of using the following BSL-1 guidelines taken and adapted from UCSD
    a. “Liquids: Add bleach to liquid waste to a final concentration of 10% bleach. Let sit for 30 minutes, then dispose down the sink”
    b. “Vacuum flask: Add bleach to vacuum flask before aspirating liquid waste. Final concentration should be 10% bleach”
    c. “Solids: Dispose of solid waste in double red biohazard bags both labeled with address, that are held in rigid, covered containers with biohazard labels. Transport to biohazard collection area in a closed rigid container for final disposal” by UVa EHS
    d. “Surface Decontamination: Use 10% household bleach solution or other appropriate surface disinfectant. Allow 5 minutes of contact time before wiping area”

Results

Due to the COVID-19 pandemic and its repercussions, we were unable to construct a physical prototype and test its effectiveness. The physical prototype would have been based on the design drawings detailed in the following sections.

A Design in Detail

A Description of the Selected Concept

The rationale for UV-C radiation in the U-bend of the sink is the elimination of the pipe climbing bacteria before they can reach the point that will infect patients. The U-bend of the pipe provides an excellent place for the pipe climbing bacteria to live due to the fact that it always contains water, and sediment and other particles tend to settle at the bottom. One key factor in our design is the use of the UV-C light on the outside, rather than the inside of the device. This provides an easy method to change the bulbs without having to reach into the sink or disassemble the sink plumbing. This also provides the added advantage that the UV-C emitting device does not have to fit in the U-bend, making cheaper, more commercially available bulbs a viable option. The idea of using the UV-C light on the outside also does not restrict water flow, and makes the use of waterproof electronic designs unnecessary.

The use of an exterior bulb does cause several new engineering design challenges. First, and most importantly, it needs to be able to direct the germicidal radiation on the actual contents to have any effect. This ability is limited by the fact that most U-bends are opaque and glass and plastics, though transparent in visible light do not transmit UV-C light. This necessitated the implementation of either a U-bend made out of a material that can transmit the light, or a "window" of some sort to allow the light to be projected into the U-bend. Based on these requirements, two materials fit the optical needs of the design: synthetic sapphire lens and quartz glass. Sapphire, though effective, was found to be less optimal than a quartz glass lens. This was decided for two main reasons: quartz glass is cheaper and provides a better medium for transmission of the UV-C light.

A second main concern faced by having an exterior UV-C emitting light bulb is human exposure to the radiation. The light emitted is a high-energy low wavelength UV light, normally most humans will mostly face UV-A and UV-B light which are lower energy and longer wavelength. The high energy electromagnetic radiation from UV light can cause burns and cell damage, and the UV-C specific wavelengths are much more harmful and can also lead to blindness. This complication has led to the necessity of a design that seals the light from the outside to prevent accidental exposure, the way our design accomplishes this is by simply containing the device in an opaque box. This simple solution provides a relatively cheap alternative to finding an effective filter or painting over sections to avoid light from leaking out. The lack of materials that effectively transmit the UV-C light enables a flexible range of materials to be used. This box must be sealed to prevent the exposure to the light and to prevent ozone produced from escaping.

This design also must be compact enough to fit underneath most sinks and in the U-bend of most sinks. This necessitates for the space of the device to be utilized well, and sets a rough size limit on our device. Another key design consideration that this project was the price considerations of our application and product. In order for this device to be utilized, it needed to be affordable for hospitals and easy to maintain. This device achieves this by being relatively inexpensive to produce, material costs for this project are estimated to be just under $150, and relatively cheap to maintain. The lightbulb will need to be replaced routinely and the quartz glass interior of the pipe will need to be cleaned. Several observational studies still need to be conducted to establish guidelines on the time between cleanings and lightbulb changes, however this will require an analysis of sediment buildup and device lifespan.

Design as an embodiment of requirements

Based on the assigned weight of each product requirement in the decision matrix created and the sensitivity analyses conducted prior to my joining of the group, UV light purification was chosen because of its strong scores in cost and effectiveness. With regards to cost, the most essential requirements mandated was minimization of the number of additional personnel to manage new systems and staying with the hospital’s allocated funds to fight HAI. The acceptable and ideal requirements for these requirements were 1-2 people per hospital and no additional personnel and 50% and 30% of the hospital’s allocated funds to fight HAI respectively. Our group of three aimed to construct a successful prototype with a maximum budget of $400. With regards to effectiveness, the most essential requirement we mandated was elimination of bacteria in the wastewater. The acceptable and ideal requirements for this was 85% elimination and 100% elimination respectively. UVC radiation is known to kill bacteria in standard settings such as the purification of food and drinking water but the discrepancy between the acceptable and ideal lies in the fact that it is unsure how effective our prototype will be given that UV radiation is being used in a novel way. This percent elimination can be quantified by culturing bacteria swabbed from the interior of the sink-trap input at the intervals specified in the procedure and calculating the percent decrease. The cost-effectiveness of the solution concept was prioritized because a solution that is productive in relation to its cost is more likely to be adopted by hospitals.

Solution Concept Diagrams

With regard to the design of the implementable solution, methodology will be followed from previous descriptions of assembly. Included within this section are two-dimensional and three-dimensional viewpoint renditions of the U-bend structure as used within the group's solution concept. The figure below visualizes a basic U-bend structure setup labeled with common included parts and features within a functioning U-bend.

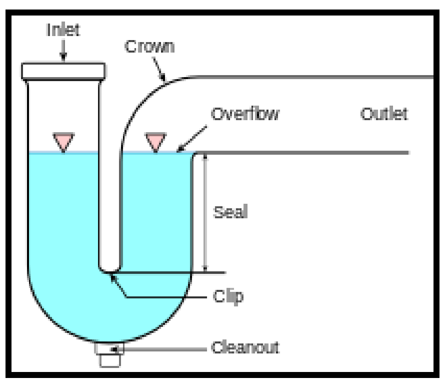


Figure 2.10: Component Overview U-Bend System

A focus of this figure is the cleanout system embedded into the bottom of the U-bend that allows regular draining and cleaning of the U-bend system from the base of the structure. This cleanout system provided inspiration for the solution concept proposed by the group, in which the UV light irradiation device will be instead introduced to the U-bend system substituting the cleanout system within this figure. Provided below are the dimensions set for the construction of the U-bend system given standardized and industry certified measurements for the proper structural integrity of the U-bend given its curvature.

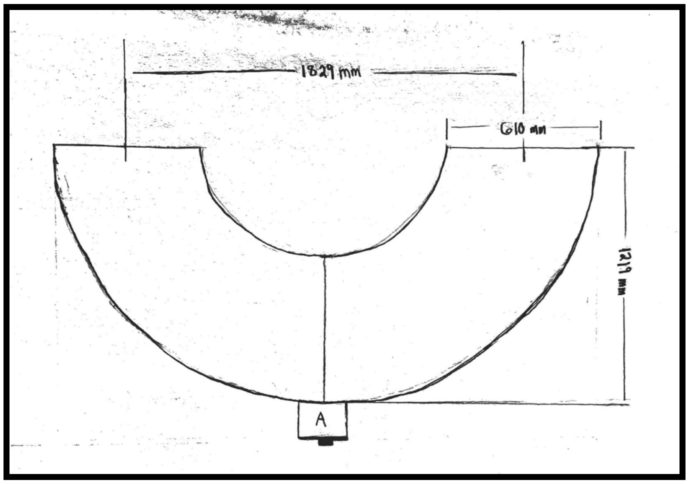


Figure 2.11: Dimensional Layout of U-Bend System

These measurements are emphasized within the construction of the system because it allows for proper demonstration of industry and STEM requirements as well as for the replication of the experiment from other parties by specifying the dimensions of the U-bend being used within the experiment. The below figure represents an exploded view of the design.

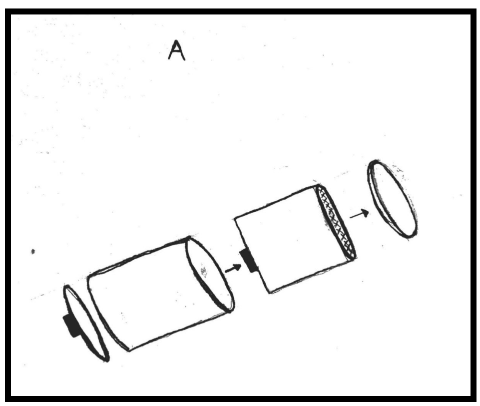


Figure 2.12: Close-Up Breakdown of Solution

From left to right, the four components are: the end cap, the body capsule, the UV light, and the quartz glass lens. This device will be put in place at the bottom of the constructed U-bend. All individual parts shown will be encapsulated within the device before integrating it into the bottom of the U-bend to begin experimentation and irradiation of the bacteria grown. A three-dimensional concept design of the solution is provided below rendered within AutoCAD

Inventor for the purpose of visualizing the system as a whole based upon the specified dimensions and components of the design.

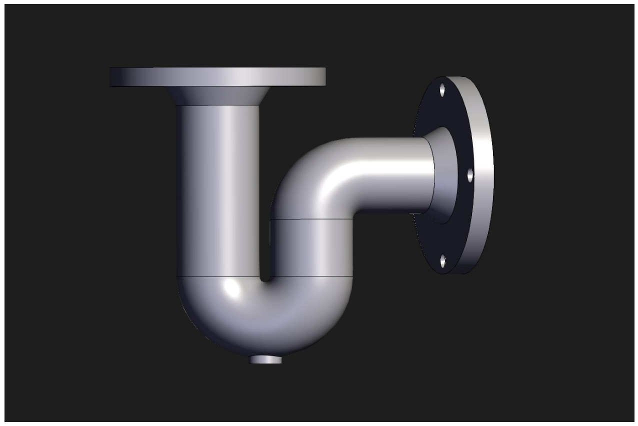


Figure 2.13: Integrated System Design 3D Model

Reflections on Design

An assessment of design viability

My personal judgment is that the concept is plausible due to the scientific basis behind it. Shortwave ultraviolet radiation is known to cause DNA damage and have sterilizing effects on microorganisms. I am more dubious about the design itself because even had testing been possible, I doubt it would have been a smooth process unless there was oversight from a subject expert as no group member had extensive experience with microbiological culture. One of the shortcomings of this design was that there was little input from design experts and this lack of corroboration from individuals well-versed in the field may have led us to make design choices that may have been scientifically uninformed. Despite these misgivings, I believe that this design merits further investigation due to the real threat of hospital-acquired infections.

Recommendations

If work on this project were to continue, the first priority would be the construction of a prototype and performing experiments to obtain a conclusive answer that the concept is viable or implausible. The design for the setup produced in this document remains in a state of uncertainty for two reasons: it is unsure how effective it will be in practice and whether this project will ever be taken up again. In the best-case scenario, the design becomes a success and it can be fine-tuned with respect to determining how the minimum duration of time the bulb needs to stay on to reach a desirable effect and how this can be automated. Minimizing this will decrease energy usage and consequently require less maintenance. If the design is ineffective, then it at least highlights the need for innovative strategies to deal with hospital-acquired infections due to the financial cost and life cost they involve.

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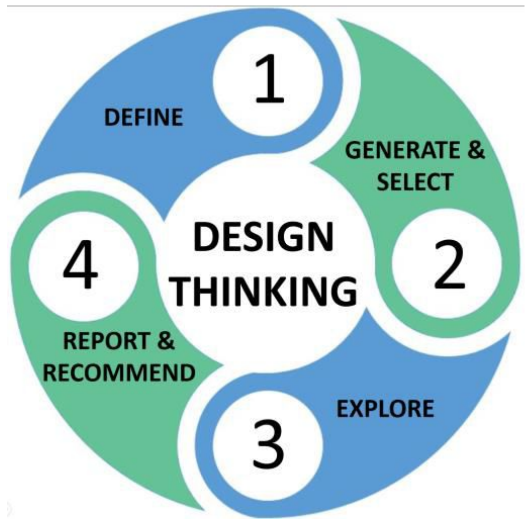
Appendix

Reflection on the design thinking process



I believe the design thinking process is a valid approach to engineering. Engineers must not only be able to derive solutions to problems but they must also clearly define these problems. Definition is the first step of the design thinking process and rightfully so as it aids in the comprehension of the challenge space and its surroundings. An engineer must be able to understand a problem before coming up with solutions to it and communicating these solutions to others. My difficulty with this step was the sheer amount of information that existed with regard to the challenge space. Trying to cover everything runs the risk of leaving certain areas underdeveloped while focusing on the most important aspects may neglect underlooked areas. Furthermore, determining what is "important" can be a subjective task rather than an objective one, which was where the next step of the process came in. Generate and Select sought to name as many requirements, metrics, and solutions as possible with the intention of trying to empirically determine what solution is the best based on its requirements and metrics. Explore is ultimately where the abstract becomes physical as designs become prototypes that can be assessed. This step was ultimately cut short but it highlights the importance of actually performing experiments and obtaining data that could be analyzed. Report and Recommend brings together the work from the past school year for a synthesis that represents the life cycle of an idea. The output from the explore step can be analyzed and either be improved on or scrapped in favor of a new idea. Both these outcomes show that the design thinking process is a cycle that continues indefinitely as the challenge space can be adjusted as seen fit in order to improve existing ideas or generate new ideas.

I personally found it challenging due to the open-ended nature of each step of the cycle but I can clearly see its usefulness. After attempting both projects, I have come to the conclusion that I should have investigated a challenge space that aligns more strongly with my areas of study. My background consists of minors in computer science and biomedical engineering, but I felt that my biomedical engineering knowledge was somewhat lacking with regard to the hospital-acquired infections project. Additionally, my main interest lies in computer science and this knowledge was rarely used if at all in both projects. Thus, the completed capstone depended nearly entirely on external research conducted in the past school year. Ultimately, a capstone that reflected my areas of study and demonstrated the technical skills and knowledge gained in the past four years would likely have been more fulfilling and reflective of my undergraduate experience.