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Road Map of Autonomous Vehicle Service Deployment Priorities in Ann Arbor

Gregory A. Keoleian, Lidia P. Kostyniuk, Tulga Ersal, Cory Wydysh, Geoffrey Lewis, and Jeffrey L. Stein

CENTER FOR
SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

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Prepared for:

University of Michigan Mobility Transformation Center

Gregory Keoleian, Lidia P. Kostyniuk, Tulga Ersal,
Cory Wydysh, Geoffrey Lewis, Jeffrey L. Stein

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Executive Summary

This report assesses the opportunities within Ann Arbor for the deployment of fully autonomous vehicles (AV) and provides recommendations on which AV systems can potentially enhance sustainability of personal transportation. Throughout the course of this research, we assume automated driving capabilities have met both technical and legal requirements to ensure safe and effective fully self-driving operation on public roads (NHTSA level 4, SAE level 5). We develop a multi-disciplinary research framework to understand the broader impacts of AV systems across various dimensions. This approach involves determining the travel demand for a proposed service based on trip behavior via existing modes, designing and optimizing an AV fleet according to the service's demand profile and drive cycle, and evaluating the AV system, and its competing modes, across a set of sustainability and system performance metrics.

Our approach can be summarized as follows. The travel demand analysis uses household survey data to determine the number of trips taken between the traffic analysis zones (TAZ) of interest. From there, we estimate what percentage of those trips are taken via public transit to obtain the travel demand for the bus route we chose to investigate. The demand estimation also yields valuable insights into routes and regions that are appropriate for AV systems. We conduct the powertrain analysis by designing internal combustion engine vehicle (ICEV), electric vehicle (EV), and hybrid electric vehicle (HEV) configurations for a typical light-duty sedan, optimizing component sizes and controls according to the route's specific drive cycle, and estimating their respective fuel economies. With both the supply and demand components defined, we assess the systems according to a set of sustainability and system performance metrics.

We apply elements of our framework to a case study of the Ann Arbor Area Transportation Authority's (AAATA, locally known as TheRide) bus transit Route 13. Quantitative evaluation of the AV system was limited to two key environmental sustainability metrics, energy consumption and greenhouse gas emissions. Through this analysis, we find that replacing the bus currently serving Route 13 with three electric AVs yields significant life cycle energy and emissions savings while maintaining sufficient rider capacity for the route. These sustainability improvements primarily come from improved fuel economy of the smaller, electrified AVs. Further, designing an AV to operate specifically within a city allows for significantly lower power requirements from the propulsion system, yielding greater energy savings. A high capacity transit bus with low fuel economy is not an efficient vehicle for this low-ridership route. A detailed financial analysis of AVs including sensing, computing, navigation, and advanced powertrain technologies will be critical to evaluate the financial and economic outlook for potential future deployments.

We create a list of the most viable candidate AV services in Ann Arbor, along with a sequence of how these types of services might be deployed. The list of candidate services considered is provided in Table ES-1, including notes regarding opportunities and limitations. We find that private single passenger AVs do not offer substantial improvements in energy consumption or congestion, and travel that is more convenient may actually stimulate more frequent and longer trips. We recommend prioritization of shared AV deployment to most efficiently utilize transportation resources and enhance sustainability. The recommended sequence for deployment is shown in Figure ES-1. Replacing buses on low-ridership fixed routes with smaller, multi-vehicle AV fleets can yield operating energy and cost savings, especially when offered as a demand-responsive service. A fixed route service is chosen as the first stage of deployment due to its minimal requirements for mapping and navigation. When such capabilities are advanced, AV systems providing service from a fixed point to a flexible set of locations within a constrained operating area can be the next stage of deployment. This stage allows some form of rider interaction with vehicle navigation, as riders choose from a set of locations that the AV has familiarity with, but the AV still must make more complicated routing decisions. When all required networks and infrastructure, such as mapping and routing and ride-hailing platforms are sufficiently developed, a point-to-point taxi service can be provided throughout the city.

These recommendations are intended to guide municipalities, fleet operators, and other key decision makers toward a systems-based approach when considering AV implementation on public roadways.

Table ES-1: Evaluation of AV Deployment Options, with Recommendations

Service	Pros	Cons	Recommendation
Amtrak	Inc. transit ridership Less parking need	Taxi, Uber competition	For low ridership (on-demand)
Bioresearch/ UM-VA	Operations energy	Assistance needs AAATA competition	On-demand
Bus Route	Op. energy, comfort wait time	Range req./fueling Larger fleet, more VMT	For low ridership (on-demand)
Intra-zone	Op. energy if shared Reduced need for parking	Difficult to share Taxi, Uber competition	Yes
Last mile	Wait time, Inc transit	Difficult to share	Yes
Night Owl	Op. energy, wait time	Security, Sensing challenge	No
North-Central	High load factor	Already served well Congestion	No
Park & Ride	Inc. transit ridership Wait time	Taxi, Uber competition Low opportunity to share	Yes (off-peak)
Senior	Access	May need assistance	Yes (able-enough)

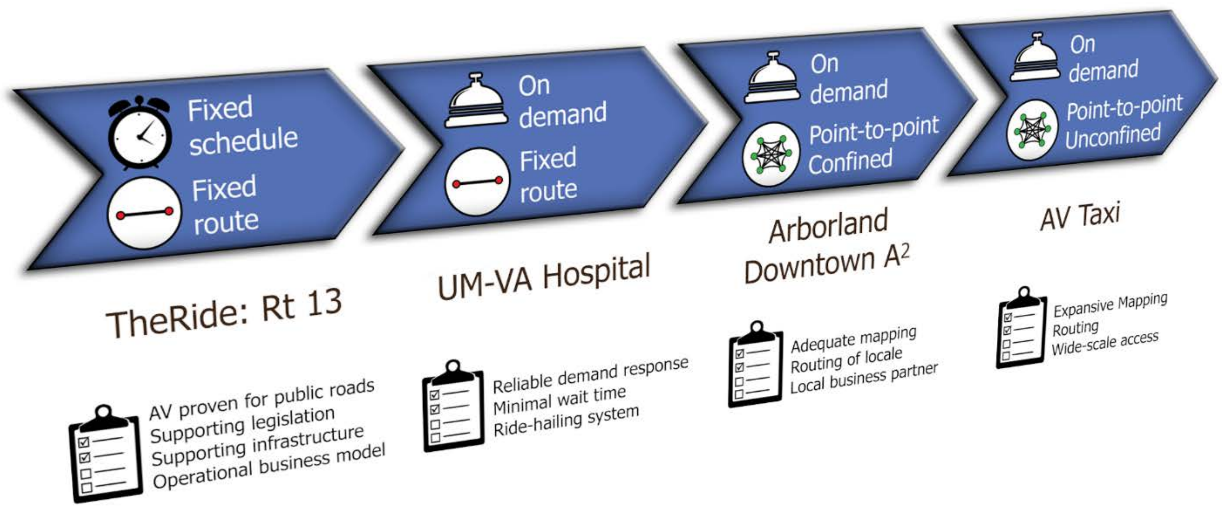


Figure ES-1: Progression of AV systems, example of service and requirements

1. Introduction

Autonomous vehicles have become a significant research topic (Kim 2016, Mosquet 2015, Naughton 2015, Zmud 2015, Litman 2014, KPMG 2012). The emergence of large-scale automated mobility is becoming a reality now, as vehicles with Advanced Driver Assist Systems (ADAS) are available in the personal car market in growing numbers.

As research efforts are devoted to questioning when AVs will come to market, it is also important to question how these vehicles will be deployed. The way in which AVs are integrated into our current transportation systems will be critical to how effectively they can enhance overall mobility. When considering the possible scenarios of AV deployment, significant trade-offs emerge. A personally-owned AV can significantly improve the safety and convenience of trips, but the cost of such a product restricts these benefits only to those who can afford them, and they may induce increased travel demand and congestion. A shared AV system, deployed by some public entity, may be theoretically more energy efficient than other strategies, but its sustainability improvements may be limited if some inconveniences hinder large-scale utilization. Given the complexity underlying these sorts of decisions, this report describes an exploration into the trade-offs that define how autonomous vehicles can enhance mobility by applying a comprehensive mobility assessment framework to a realistic deployment scenario. The insights gained from this investigation are then used to suggest best practices for AV deployment in the near- and far-term for the City of Ann Arbor, Michigan.

This project is part of a larger initiative within the Mobility Transformation Center (MTC) at the University of Michigan to "pull together the diverse expertise and resources required to realize the unprecedented potential of this emerging technology, culminating in the implementation of a working system of connected and automated vehicles in Ann Arbor by 2021" (MTC website). The underlying research to achieve MTC's mission is broken down into the three "pillars" defined below:

- Pillar 1: Connected Ann Arbor (2014+)
  - 9,000 equipped vehicles
  - 27 sq. miles of equipped infrastructure
- Pillar 2: Southeast Michigan Connected Vehicle Deployment (2015+)
  - 20,000 equipped vehicles
  - 500 equipped nodes, including highways and intersections
  - MDOT smart corridor
  - 5000 devices including nomadic seed devices, extending to vulnerable road users such as pedestrians
- Pillar 3: Ann Arbor Automated Vehicle Field Operational Test (2016+)
  - 2,000 connected and automated vehicles
  - Including Level 4 automated vehicles
  - 27 sq. miles of densely instrumented infrastructure

The Pillar 3 objectives include significant deployment of AVs in Ann Arbor. In order for this deployment to take place, one must consider the most viable strategies for AV deployment and identify which of those leads to the greatest mobility enhancement. Through our interdisciplinary research, we aim to provide a new framework to evaluate mobility systems that can appropriately account for unique issues brought about by AVs. This framework is intended to be unbiased towards any transportation mode, and must therefore address mobility performance in a comprehensive manner. In developing such a framework and applying it to specific examples of potential deployment scenarios, we are able to draw conclusions on preferred AV strategies versus common existing modal options (personal vehicle, public bus route, etc.).

2. Analysis Framework

Integrated Framework

In analyzing the potential for autonomous vehicles in Ann Arbor, a multidisciplinary approach must be taken. As shown Figure 1 below, the travel demands of the area must be considered, along with assumptions of how AV systems may affect this demand (component A). Defining the mobility needs that an AV system aims to serve is critical to designing the system. For instance, if there is particular interest in serving an area with frequent high levels of travel demand, selecting higher capacity vehicles may be necessary. Deciding what type of vehicles are chosen for the AV fleet is a critical consideration (component B). In order to understand what AV systems would better enhance sustainability and mobility, a sustainability assessment must also be conducted (component C). These components are interrelated, as parameters such as system scale and vehicle powertrain can directly affect sustainability performance. Within this framework, our analysis aims to identify the key drivers for sustainability performance by comparing different mobility systems and uses those findings to develop recommendations for deployment strategy.

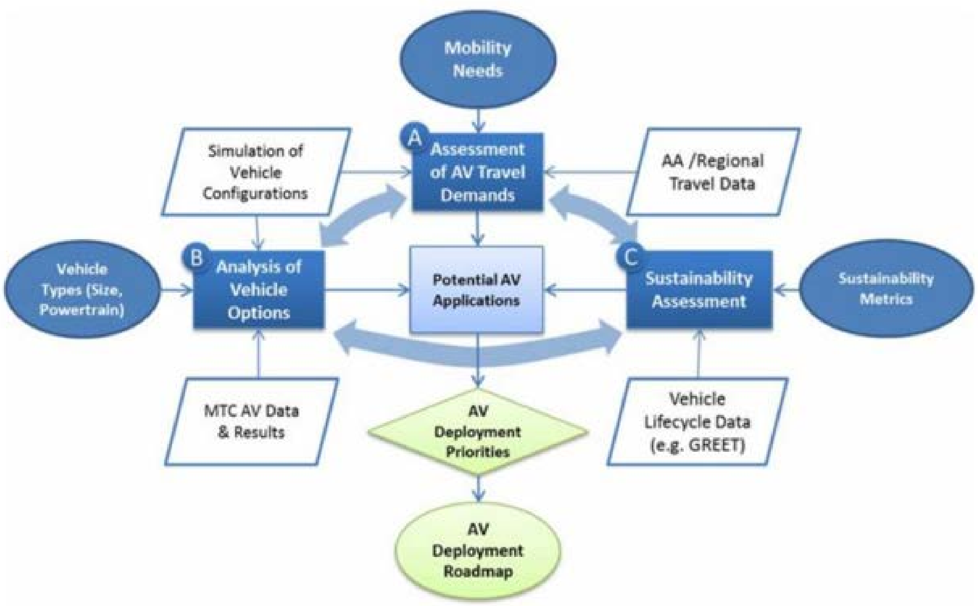


Figure 1: Analysis Framework for Potential AV Applications

Analysis Components

Supply and Demand Characterization

Designing an AV system involves identifying many considerations and specifications. These system characteristics involve several realms, including temporal and geographical boundaries, operational controls, and the necessary digital and physical infrastructure. Changes to such parameters lead to variations in system complexity, which may inhibit the accurate simulation of such a system. For the purposes of this study, maintaining a relatively simple mobility scenario allows us to assess the analysis framework as comprehensively as possible. This section attempts to identify all appropriate AV system parameters that may be included in design and simulation and how differences in these parameters impact high level AV system performance and both real-world and modeling feasibility.

2.1 Supply Analysis

The set of parameters used to characterize the supply of these mobility systems is intended to identify the differences between systems. Table 1 provides an example set of parameters used when comparing transportation systems. Properly contrasting the mobility systems is essential to understanding correlations between key system characteristics and disparities in performance across a robust set of metrics. The defining supply parameters can be broken into two categories of fleet/vehicle design and operations. We distinguish between these two different types of parameters to assess relationships between impacts on sustainability performance and particular supply characteristics. For example, are lower emissions per passenger-mile due to electrified powertrains, smaller vehicles, or better utilization?

Table 1: Example of Supply Characterization Metrics

Metric	**Unit**
Fleet Size	Total Vehicles
Vehicle Size	Seats/vehicle
Total Fleet Capacity (Availability)	Total Seats
Fuel Economy	MPG, (MJ/mi)
Fleet Diversity	# of significantly unique modes
Access of Service	# of AV stations, apps, etc.
Service Time	min, hour

2.1.1 Vehicle Design

A critical aspect in the performance of an AV system is the fleet composition. The fleet size, vehicle size, heterogeneity, and powertrain are all key contributors towards how well AVs are utilized, as well as their performance. Optimizing the fleet and vehicle sizes and propulsion system can help realize the potential economic, environmental, and social benefit of a system by efficiently applying transportation resources. Understanding the exact function of the vehicle and both the magnitude and frequency of expected travel demand aids in the design process. A vehicle meant to serve a small number of riders can be minimally sized, while higher and more variable demand would require either larger vehicles or additional fast responding AVs in order to adequately serve more intense travel demand periods.

The legal guidelines for, and physical infrastructure within, a specific roadway are particularly influential in terms of powertrain, safety, and other vehicle design requirements. If speed limits of a given AV service area are limited to 35 mph, vehicles with lower power propulsion systems can be implemented. These sorts of scenarios may also lead to exceptions in vehicle licensing and certifications, such as airbags, brake lights, or other safety requirements. Large non-technical challenges to high speed operation exist, both from a liability standpoint and from less stringent general regulations for low speed vehicles in general and neighborhood electric vehicles in particular (US DoT) (NHTS). The difficult legal and liability environment, a concern for AVs in general, could be partly ameliorated by low speed operation. This point is further bolstered by the general uncertainty surrounding AV safety benefits and the likelihood that low-speed operation would offer a more controllable and predictable safety environment; a failsafe command to stop a vehicle works reasonably well at low speeds, but less so at highway speeds.

The expected daily range of a vehicle (along with available refueling stations) affects battery and fuel tank sizing in fleets, helping determine which sort of powertrains operate most efficiently. Selecting the most appropriate powertrain in order to maximize fuel economy and emission reductions, while still weighing cost-effectiveness, is another essential consideration in designing an AV fleet.

Finally, it is important to identify the amenities desired by riders to encourage utilization of AVs. These amenities may include bike racks or cargo space, or perhaps infotainment systems. Regardless of what is included in the vehicle, it is important to determine what amenity is worth the cost of implementing in terms its effect on vehicle occupancy and utilization.

Initially, it seems reasonable to consider a simple homogeneous fleet when designing a particular mobility service, but in the long term, heterogeneity allows an AV fleet to provide other sorts of services and to better accommodate demand fluctuations in magnitude (i.e., number of passengers) and type (e.g., trip to mall in the neighborhood versus trip to airport).

The design of the vehicle powertrain significantly influences the fuel economy and emissions, thereby directly impacting the economic and environmental sustainability of a shared AV fleet. Powertrain design involves three main levels: structure, component sizing, and control. The structure of a powertrain refers to how the prime movers are connected to each other and to the wheels. Examples include conventional powertrains powered by an internal combustion engine, electric vehicles that rely solely on a battery as the power source, or hybrid powertrains with various configurations of an engine and battery. The component sizing problem refers to the proper selection of sizing parameters such as electric motor power, engine power, battery power, and gear ratios to ensure that the vehicle functions efficiently and performs well. Finally, powertrain control is the manner in which a system of prime movers is coordinated to execute a task. Optimal design of a powertrain necessarily requires consideration of all of these three levels.

Traditional vehicles are designed to perform well across a wide spectrum of conditions, ranging from city driving to highway driving, from aggressive driving to smooth driving, from short trips to long trips. However, if a particular initial deployment scenario for an AV fleet results in a very well-defined, narrow set of operating conditions such as circling a predefined route at low speeds, then taking an existing vehicle and utilizing it for such a shared AV deployment may not be the best choice from both an economic and environmental perspective. Instead, information about the specific operating conditions can be used to optimize the powertrain of the vehicles to maximize their economic and environmental sustainability. To this end, frameworks that can perform powertrain optimization at all three levels simultaneously are needed.

The rationale for having a systematic framework stems from the fact that the design space is large and all three levels are interconnected. As a result, finding the optimal solution by intuition or in an ad-hoc manner is infeasible. For example, an electric vehicle may look like the ideal solution from a fuel economy perspective. However, providing continuous service with a fleet of electric AVs may require a very high capital cost: recharging requirements during high use periods means that more electric vehicles are necessary than if the same demand were met with a fleet of conventional or hybrid AVs. Thus, vehicle design decisions are also coupled with fleet size and operation decisions and fueling options.

2.1.2 Operations

Operational aspects to consider are routing (both geographically and temporally), fleet size, and infrastructure requirements. In regards to the geographical parameters of the AV system, it must be decided whether a fixed route is being followed or if there is flexibility to the routing choices of the AV system. This consideration raises an issue of comparison. For instance, if an AV system can take passengers directly to their doors, this system is providing an additional "last-mile" service that was not provided by the baseline system. In order to make a more equitable comparison, the analysis scope must be expanded to include the "last-mile" leg of this tour, which is most often provided by walking in the typical baseline scenario. These differences in operational service must be acknowledged and accounted for when comparing transportation systems.

An AV system can theoretically operate continuously throughout the day with no change in service. However, comparing different types of mobility services across a set of metrics requires some parameters, such as service hours, be held constant. Since AVs have not yet demonstrated the ability to operate reliably after sundown, limiting analysis to daytime is more realistic considering current AV operational characteristics. When considering other time-dependent operations of a mobility service, the level of demand-response is essential for differentiating between systems. In considering a maturely developed on-demand AV system, it is possible that response to trip requests will be quicker and waiting times will be shorter than in a scheduled AV system. This difference in convenience may define how widely such a service is adopted, impacting operational efficiency of the system. Ensure customer satisfaction by minimizing wait times may require larger fleets, increasing the overall cost of the system. If these costs increase fare prices beyond a rider's willingness-to-pay, then the service is less likely to have participants.

2.2 Demand Analysis

It is important to identify the key differences in demand for various services when comparing mobility systems. Many of these differences exist in both the time and space domains, so specifying these parameters will allow a clearer understanding of the basis on which services are being compared. Either developing a realistic simulation or implementing measured travel demand data can enhance the accuracy of system performance computations. Socioeconomic development in the study area of its surroundings can drastically change travel demand. It is important to evaluate the systems according to the same travel demand, so normalizing by passenger-miles-traveled (PMT) may be necessary to yield an "apples-to-apples" comparison. However, it is difficult to project new demand for an AV mobility system, as mode choice models incorporating AVs have not yet been developed. Understanding demand for, and best utilization of, AVs is critical to developing a convincing and economically viable business case for these systems. Table 2 below provides an example of some demand-side parameters that may considered when analyzing and comparing different transportation systems.

Table 2: Example of Demand Characterization Metrics

Metric	**unit**
Service Area	mi^2
Population density	people/mi^2
Travel Demand	# of person trips
Peak Travel Demand	Max # of person trips
Travel rate	#person trips/hr
Employment Density	# jobs/mi^2

Conducting a demand analysis for a particular route or transit service can guide how AV fleets are designed based on the capacity required to service current demand. To assess whether AVs would be appropriate for a particular region or service, it is essential to understand not only the current demand for travel within that region but also the degree to which demand is likely to increase due to new, more convenient modes tapping into latent demand.

2.3 Sustainability Assessment

2.3.1 Sustainability Metrics

To ensure a proper sustainability assessment, the definition of sustainability must be considered. The key aspects of Brundtland's definition are economic development, environmental protection, and social equity (Brundtland et. al. 1987). Particular metrics can serve as indicators of performance for each of these dimensions of sustainability. While selecting performance measurements for any sort of transportation system can be subjective, it is our intent to provide an unbiased analysis, aimed at providing insights on how the disruptive nature of AVs can best serve the common good. With this intent in mind, we constructed a comprehensive set of sustainability metrics that considers the interests of all entities across many dimensions, including time. An AV mobility system should benefit riders, operators, and other current and future road users. Commonly used metrics from the literature and existing transportation sustainability programs were selected to measure sustainability performance (Jeon 2013, Joumard 2008, Litman 2008). We sought to measure the sustainability performance of various transportation systems with methods that are unbiased with respect to both modes of travel and user demographics. In order for a sustainability evaluation to take place, metrics that capture the criteria most important to all stakeholders must be chosen. This multidimensional framework of metrics follows the principles of sustainable development, considering the economic, environmental, and social impacts on present and future generations.

Vehicle automation can be integrated into future transportation systems in a number of ways. Two fundamental characteristics that have can have significant implications toward sustainability enhancement are private ownership and shared vehicles. Shared AVs, through increased utilization, can improve transportation sustainability by having shorter lifespans, allowing newer, more efficient vehicles to take their place. This rapid replacement may seem counterintuitive, as manufacturing vehicles is costly and energy intensive, however a large majority of a vehicle's life cycle energy consumption occurs during the use phase (burning fuel) (Chester and Horvath 2009).

In addition to sharing vehicles, ride-sharing can lead to further improvements in sustainability performance by removing vehicles from the road (Zhang 2015). However, a balance must be achieved between sharing rides and efficiently routing trips to minimize riders' distance and time traveled. If ride-sharing becomes too inconvenient due to longer trips, rider participation will be low.

Beyond considering AVs as a sole mode of travel, they may also be used to supplement existing modes. Moorthy et al. (2015) describe the potential for AVs as a last-mile solution, providing both cost and energy savings over other single and multi-modal options. In addition to the benefits AVs have over other modes, first/last mile service provided by AVs can facilitate increased public transit use as another opportunity to enhance transportation sustainability.

Economic success of a transportation service requires the service to be inexpensive enough to maximize a ridership base and not hinder travel. The service must also generate revenue to cover the costs of operation, as well as to support maintenance and system improvements. The main economic objective is providing the lowest cost mobility without sacrificing quality of service, and thus rider participation. The initial capital required to build the transportation system determines the viability of a new project. If an AV system cannot be properly financed to ensure reasonable upfront costs, organizations would be hesitant to collaborate on this potentially risky venture. In addition to capital costs, total operating costs of the system (fueling, licensing, and insurance) must be identified. Travel costs are often quantified beyond the prices to own and operate vehicles or simply payments for a ride service. These costs influencing the fare price may be reduced through government subsidy, as is the case for most public transit systems. Other methods of valuing these systems may include externality costs if more stringent environmental regulations (on tailpipe emissions, for example) force fleet operators to invest in R&D or alternative fuels. Inclusion of value of time (VOT) helps better realize the monetary benefits or costs of transportation modes. Several studies have shown that considering these time values along with vehicle-sharing business models significantly reduces the cost of travel on per-mile basis for AV fleets compared to conventional transportation modes, such as public buses, trains, or even personally-owned vehicles (Burns 2013). Table 3 contains economic sustainability performance metrics and their associated units.

Table 3: Economic Sustainability Performance Metrics

Metric	unit
Capital Cost	$/PMT
Operating Cost	$/PMT
Fare Price	$/trip,(trip-mile),(PMT)
Ridership	trips
VOT Savings	$/min

Environmental impact of mobility is dependent on how much traveling is done by any given mode, and is proportional to VMT, but the set of metrics should not preference trip length or modes used in a trip. For an analysis framework to be applicable to many different modes, locations, and trip types, metrics must also be based on readily available data. The set of environmental metrics chosen, shown in Table 4 below, focuses on higher level quantities and carbon dioxide emissions and steers away from highly variable atmospheric chemistry metrics that would be difficult to measure. An obvious precursor to calculating CO_2 emissions is to find the fleet's energy consumption, although it is important to distinguish the emissions source, as electrified powertrains have varying emissions attributed to them based on the fuel used to generate electricity (Anair and Mahmassani 2012). Similarly, oil consumption should be quantified separately to reflect depletion of a non-renewable resource (Litman 2008). Additional long-term impacts such as land use could be included when data on AV adoption rates and demand are more reliable.

Table 4: Environmental Sustainability Performance Metrics

Metric	unit
Energy Consumption	MJ/PMT
Emissions	kg CO_2/PMT
Oil Consumption	Barrels of oil/PMT
Fleet Distance	VMT
Fleet Fuel Economy	MJ/mi
Land use impact	mi^2

Many of the metrics pertaining to how mobility systems affect society are difficult to calculate, so comparing scores may have to rely on data collected retroactively. Metrics such as operating costs and energy consumption can be predicted or simulated with reasonable accuracy, but no reliable method exists for predicting the number of AV traffic incidents, the AV adoption rate, or how AVs will change travel demand. Vehicle automation is expected to reduce traffic incidents by removing human error, as the driver is at fault in 94% of crashes (NHTSA 2015). The degree to which AVs can improve safety and traffic flow largely depends on their penetration. One AV on the road will have little to no effect besides on the vehicles immediately surrounding it, whereas a road occupied only by AVs can have optimal traffic flow due to driving behavior programming in every vehicle and communication between them. It is important to track adoption rates and road fleet penetration rates along with the travel modes riders are shifting away from. AV services providing mobility to those who cannot operate a vehicle or have no access to public transit is a potential societal benefit (Zachariah 2014). Disabled people and young people will have an easier time getting to work, while car and cab services will most likely see a reduction in use (Zmud 2015). These changes can only occur if a convenient, affordable, accessible, and enjoyable service is offered, with convenience implying that wait times are a critical factor for AV adoption. Social sustainability metrics are collected in Table 5 below.

Table 5: Social Sustainability Performance Metrics

Metric	**unit**
Travel time	min
Impact on travel demand	# trips/person
Total motorized movement of people	PMT
Access to mobility service	# people < 1 mi to station
Wait time	min
Safety	incidents, injuries, fatalities/PMT
Impact on non-motorized travel	Non-motorized PMT
Impact on traffic flow (congestion)	real travel time / free-flow travel time (Travel time index)

2.3.2 System Performance Metrics

Just as design parameters can be critical to particular sustainability metrics, broader system efficiency definitions can drive sustainability performance in accordance with several measurements at once. For instance, increasing fleet-wide load factor can reduce operating cost, energy, and emissions per passenger-mile traveled. Performance indicators may influence a system's sustainability performance by measuring how particular resources such as time, road space, or monetary investment are utilized. In essence, these indicators are developed by considering the fundamental definition of efficiency, where the ability to achieve a desirable outcome given some input is measured. Since that the purpose of a transportation system is to move people, the distance traveled and time a passenger spends traveling are the measured outputs, while the required input is vehicle movement (which requires fuel and other costs). Measuring how efficiently resources are utilized to move passengers provides information on system sustainability performance. If vehicles are driving around empty, road space is needlessly occupied, fuel is wasted, and CO_2 is emitted with no mobility service being provided.

System performance is separated into three categories. At the vehicle level, load factor (occupancy per total capacity) is an indicator of proper vehicle sizing and utilization. Increased load factor also means more trips are served by less vehicles, indicating improvements in congestion. This metric can also be averaged across multiple vehicles to assess an entire fleet's performance, as is the case with most of the vehicle-focused system performance metrics. Other metrics crucial to evaluating system performance, such as time in service, maintenance, and refueling time, effect the vehicles' utilization (as a function of time). Among the arguments for AVs is the low utilization rate of personally owned vehicles (Fagnant 2015). It is critical for AV systems to perform much better by this measure to ensure greater overall sustainability performance, particularly for the economic metrics.

Effects of AVs on overall transportation system efficiency, such as measured by congestion, are equally important to consider. Road level of service is a common metric used to measure traffic flow. Whether AVs have an impact on this metric would depend greatly on AV penetration levels as well as changes in traffic incident frequency. Also dependent on AV penetration is the rebound effect resulting from more convenient travel. AVs have the potential to release latent demand, resulting in more frequent and/or longer trips.

The ratio of passenger-miles traveled (PMT) to vehicle-miles traveled (VMT) is central to the operational performance of an AV system, as transportation resources that are being used but are not serving passengers are wasting resources. By strategically locating and routing vehicles and sharing rides, empty VMT can be reduced to optimally utilize resources across fleets (Spieser 2014, Zhang 2015). “Effective” passenger-miles and passenger-time traveled are metrics that attempt to discern the difference between the shortest routes passengers can take (with respect to both time and distance) and the actual route traveled. This concept is most important for mobility systems with dynamic routing, such as ride-sharing.

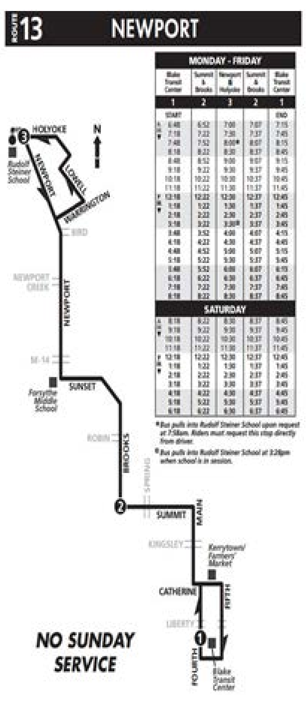
Table 6: System Performance Metrics

Vehicle	Fleet	Transportation System
Load factor	Load factor	Road level of service
Time in service	Time in service	PMT/ VMT
Refueling time	# of vehicles / (PMT or trips)	Effective PMT, PTT
Maintenance time		Rebound effect (latent demand)

3. Case Study: Route 13

A case study was developed to model an AV system using existing travel demand in order to assess the system's performance in comparison with a currently existing mode of service. The Ann Arbor Area Transit Authority (AAATA, TheRide) Route 13 was chosen as the basis of comparison between an AV system and the current bus system. Route 13 was selected for this study as it offers a strong business case for enhancing mobility by drawing travel demand (possibly latent and from other modes) towards new transportation assets that would otherwise remain underutilized. The schedule for Route 13 is illustrated in Figure 3 and a map of the route is shown in Figure 4. Existing bus service can be replaced with an AV service in variety of ways. As stated previously in the description of the mobility assessment framework, it is critical to consider the supply and demand characteristics of both services to fully understand the comparison being made and what characteristics may affect performance.

Through this case study, we apply the analysis framework described above in Figure 1. We performed a demand estimation for this route in order to understand what capacity is required to serve demand at any given time. We then optimized the AV powertrain for this route and assessed the AV system's sustainability performance through energy and emissions modeling using GREET (Argonne National Laboratory 2016) and additional high-level qualitative analysis.



MONDAY - FRIDAY				
Blake Transit Center	Summit & Brooks	Newport & Holyoke	Summit & Brooks	Blake Transit Center
1	2	3	2	1
START				END
6:48	6:52	7:00	7:07	7:15
7:18	7:22	7:30	7:37	7:45
7:48	7:52	8:00*	8:07	8:15
8:18	8:22	8:30	8:37	8:45
8:48	8:52	9:00	9:07	9:15
9:18	9:22	9:30	9:37	9:45
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6:18	6:22	6:30	6:37	6:45
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8:18	8:22	8:30	8:37	8:45
SATURDAY				
8:18	8:22	8:30	8:37	8:45
9:18	9:22	9:30	9:37	9:45
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3:18	3:22	3:30	3:37	3:45
4:18	4:22	4:30	4:37	4:45
5:18	5:22	5:30	5:37	5:45
6:18	6:22	6:30	6:37	6:45

*Bus pulls into Rudolf Steiner School upon request at 7:58am. Riders must request this stop directly from driver.

#Bus pulls into Rudolf Steiner School at 3:28pm when school is in session.

Figure 3: Route 13 Schedule

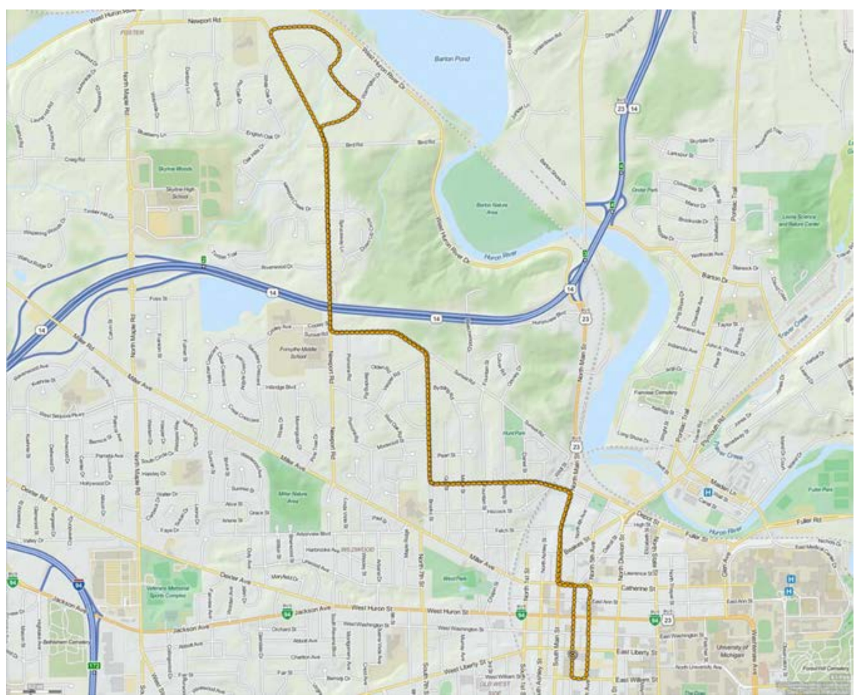

Figure 4: Route 13 Map

Route 13 operates every half hour between 6:48am and 8:45pm on weekdays and hourly on Saturday between 8:18am and 6:45pm. Although an AV service can theoretically provide mobility at any time, we limit the AV system's operation to the times in the Route 13 schedule to ensure a fair comparison with the current bus service.

4.1 Analysis of AV Travel Demand

Route 13 Demand Estimation

A critical task in this project is to estimate the number of users for the AV systems proposed in the roadmap. The relation and effect of AV on other modes has a multitude of possible outcomes on travel behavior and VMT changes (Bierstedt, Gooze, et al., 2014). It is generally recognized that the introduction of AVs systems will require revisions in standard transportation planning tools at all levels including regional travel demand models and traffic impact assessments (Smith 2012, Pinjari, Augustin and Menon 2014).

Most travel demand models in use today estimate modal distributions with economic models that consider the utility of all available modal alternatives. The key variables in these models include in- and out- of vehicle travel time and costs, together with sociodemographic variables that reflect user preferences and behaviors. Household data from travel surveys or microsimulations are used to estimate the parameters of such models. Thus, methodologies for estimating travel demand theoretically could include a new AV service in the set of alternatives available to trip makers. However, there are no real world AV applications to provide data for model parameters estimation. Although user acceptance is being studied through surveys and interviews, (e.g., Schoettle and Sivak 2014, Howard and Dai 2014, Zmud et al. 2016), it is not yet known how AVs will change travel behavior. Indeed, it is not known if the model structures or assumptions of current demand models will apply. Although estimation of demand for AV services requires information not known at this time, some initial quantification of demand for AV services that are being envisioned is needed.

While much of the current focus of the effects of AVs on the transportation system has been from the perspective of AV as a personal vehicle, it is recognized that AVs present opportunities for shared operations and public transit. An AV operation can lower costs for public transit agencies by reducing personnel costs, replacing service on low volume routes, and providing more personalized and reliable service with smaller vehicles for demand-responsive transit service. It is highly likely that AVs will change transit demand in that traditional transit captive market segments (e.g., elderly, disabled) will have other options (Bhatt and Pendyala 2015). Furthermore, transit agencies might expand the scope of their operation with demand responsive AV services similar to “Uber” or “Lyft” operations. It is also possible that future transportation alternatives will include community-based group ownership of AVs fleets or private subscription services.

Burns et al. (2013) explored the performance and costs of a shared driverless fleet in several scenarios including a medium sized US city using Ann Arbor as an example. The demand for the AV shared service was estimated by assuming that trips made by 90% of vehicles that drove up to 70 miles in a day would be replaced by trips on the AV shared service. The average number of vehicle trips per vehicle, average vehicle occupancy, average trip length, portion of trips made in peak hour trips was used to estimate of the demand for the service. The trips were assumed to be uniformly distributed over the region. Trips were requested at constant average rates for peak and off-peak periods and the time between requests was exponentially distributed. It was assumed that vehicles traveled at a constant speed, and one type of vehicle was used for all trips. Initially the vehicles were randomly scattered over the region, and vehicle requests came in randomly. As requests came in, positions of all vehicles (idle and in service) were scanned and the vehicle that could reach the requestor first was assigned to it. When a vehicle completed a trip, it either went on to another customer or waited in place until summoned.

This shared AV operation was modeled as a queueing system with vehicles as servers and trip requests as customers. Service times included the time vehicle traveled to customer, time with customer and idle time till next summons. Simulations were run with various numbers of AV fleet, and performance measures such as average, empty, and loaded travel distance, average idle time relative to in service time, average capacity utilization were calculated. The study also applied similar assumptions and methods to examine an AV taxi service in Manhattan.

The approach used by Burns et al. in their demand estimation was based on the assumptions that the service will be embraced by a large portion of the population and the basic pattern of activities and trip making will not change much from the present patterns. The information about the present patterns came from available statistics on the population and regional trip information.

Our approach

Our approach is also based on existing patterns of travel in Ann Arbor and assumptions about the proportion of person trips that the AV service will draw from existing modes. However, more detailed information about the patterns of travel within the Ann Arbor area is incorporated. The approach consists of the following steps:

- Determine the area of service
- Determine the population to be served
- Determine the trip purposes
- Obtain trip generation information in area intended trip purposes in the service area
- Determine time of day distributions of trips
- Assign a share of trips to AV service

It will be necessary to assume the share of these trips that will go to the AV service, and vary the share through worst to best case scenarios. The assumptions about shares will need to be refined as more is learned about user acceptance of AV systems, and as our transportation system changes with the connected vehicle and AV technology.

Data sources

The main source of existing travel patterns in Ann Arbor is the system of transportation planning model of the Washtenaw Area Transportation Study (WATS). WATS is a multi-jurisdictional agency mandated by federal law to provide a continuing, cooperative and comprehensive transportation planning process, which guides the expenditure of state and federal transportation funds in Washtenaw County. To that end WATS maintains a transportation planning model system to generate detailed travel forecasts The county is spatially divided into a set of transportation analysis zones (TAZ) and a database of socio-demographic and economic variables is maintained from census data and regional forecasts. Information about regional travel patterns is collected periodically through travel and activity surveys. Together these provide input to the planning models. The current WATS planning models use TRANSCAD software and consist of a trip generation model, trip distribution and mode choice model, and network assignment. A trip is defined as a one-way journey between an origin and destination (LSA Connetics Transportation

Group 2008). Trip generation models estimate trip productions and attractions between each TAZ pair for a set of trip purposes.

Figure 5: Transportation analysis Zones in Ann Arbor Area

Trip production for a set of trip purposes is estimated first at the household level using income, household size, lifecycle, and vehicle ownership, and then aggregated to TAZ zones. Trip attractions to each TAZ are based on employment, land use, and activity opportunities in the TAZ. Trips are classified as home-based or work-based, if either the origin or destination of the trip is home or work, respectively. Trips that do not start at home or work are classified as other-based. Trip purposes in the WATS model include work, shopping, university, and other. Thus, trips in the WATS model consist of home-based work, home-based shopping, home-based university, home-based other, work-based other, and other-based other. The distribution and modal choice models estimate the trip flows between the TAZs by mode using utility maximization model that calculates destination/mode with nested multinomial logit model calibrated for the Ann Arbor area. The output of these models is a production attraction (P/A) matrix for each trip purpose by each mode. It should be noted that each entry in the matrix represents a two one-way trips, i.e. out to the destination and back to the point of origin. While not exactly true, this assumption was made for simplicity and can be traced back historically to when the work trip was the primary trip of interest urban transportation planning.

The current WATS model is the most comprehensive source of existing trip patterns and traffic flows within the city of Ann Arbor. It allows estimation of changes in traffic volumes and patterns in response to changes in the roads system, available transportation services, and demographics of the population.

Other useful sources of information for estimating travel patterns include US Census, National Household Travel Survey (NHTS), (Santos et al. 2009) and from the Michigan Travel Counts surveys (MI Travel

Counts) (MDOT 2010). These sources provide information on the population, vehicle occupancy, portion of trips by transit, taxi, time of day trip distributions by purpose. Information about transit ridership can be obtained directly from the transit agency, and information about taxi use can be requested from taxi companies. For very specific and confined areas, it is also possible to obtain information about use by conducting passenger or vehicle counts studies.

Exploring possible areas for AV shared service deployment

We requested and obtained the output for the WATS transportation model for 2015. As a first step we identified the highest P/A passenger car flows within and between zones, and judged if providing a shared AV vehicle system for these flows would be in line with the project objectives.

Figure 6 shows TAZ with high trip generation for passenger cars. The squares mark the TAZs with highest P/A flows between zones. The TAZs marked with circles had the highest internal TAZ flows, that is, the trips were made within the TAZ. To obtain the number of person trips in a day, we assume that each P/A pair is 1.5 vehicle trips and 1.8 persons per car.

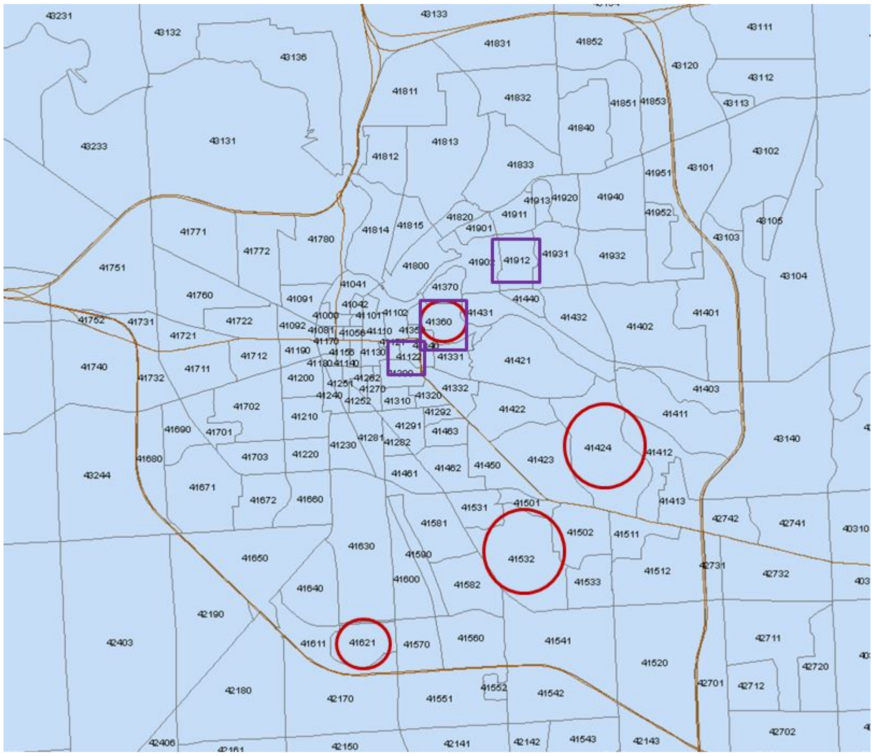

Figure 6 TAZ with high trip generation rates

From these we estimate that about, 27,000, 28,000 and 21,600 person trips enter or leave U-M’s Medical campus, North campus, and Central campus respectively each work day (Table 7). Home-based work trips tend to be concentrated in the peak periods, while the home-based university trips and other-based trips are likely to be made throughout the day. These trips are from all parts of Ann Arbor area, so the service area for would include all of Ann Arbor, but would have demand for service throughout the day.

Table 7: Ann Arbor TAZ high number of trips/day by passenger car to and from each area

TAZ	Area of Ann Arbor	person trips /day	% trips by purpose
41360	U-M Medical Campus area	27,000	21% Home-based–work 27% Home-based-other 20% Home-based-university 30% Other-based-other
41912	U-M North Campus area	28,000	80% Home-based-university 12% Home-based-work
41122	U-M Central Campus area	21,600	77% Home-based-university 14% Home-based-work

The TAZ with the highest internal flows are summarized in Table 8.

Table 8: Ann Arbor Traffic Analysis Zones with highest internal trip flows by passenger cars

TAZ	Area of AA	person/trips/day	trip purpose, greatest %
41424	Washtenaw Ave, just west of Huron Parkway	1,100	45% home-based shopping
41532	Packard Ave near Stone School	1,750	56% home-based other
41621	Briarwood Area	4,200	87% other-based-other
41360	U-M-Medical Campus area	5,940	55% Other-based-other 45% work-based other

The U-M medical campus, besides being one of the largest attractors in the Ann Arbor Area generates almost 6,000 person trips within its TAZ. Fifty-five percent of these trips are classified as other-based-other, which suggests that they are most likely made throughout the day including the off-peak periods. Other areas of Ann Arbor with high internal TAZ flows include the Briarwood area, the area near Packard and Stone School, and the area near Washtenaw and Huron Parkway. The trip purpose distributions within these TAZs have large portions of trips for shopping and other purposes, which are made throughout the day. Any of these areas could be used as an initial deployment site for a small area demand responsive shared AV service.

In our next step, we examined the trip flow patterns in Ann Arbor to identify possible deployment areas for an area-wide service area larger than a single TAZ but not encompassing the entire city. We identified the corridor connecting the U-M central, medical, and north campuses (Figure 7) as one of the possibilities. The number of person trips in this corridor by trip purpose was obtained from the WATS P/A matrix of the trip generation model output and is shown in Table 9.

Figure 7: U-M Campus Corridor Area TAZS

Extracting the trip distribution for passenger cars from the P/A matrix for the corridor and converting them to person trips using the same trip chain and vehicle occupancy assumptions as before gives the number of person trips by passenger car for each trip purpose. The time of day is assigned based on typical temporal distribution of trip purposes.

Table 9: Person-trips by passenger car /day in campus corridor

Trip purposes	Person trips/day	Time-of day
Home-based-work	2,000	morning and evening peak periods
Home- based-shopping	2,000	off-peak day
Home-based-University	23,000	all day
Home-based-other	3,600	all day
Work-based-other	15,000	off-peak day
Other-based-other	10,500	all day
Total	56,100	

Demand Analysis for Route 13 Service Area

The route is 7.5 miles long (roundtrip), and runs from the Blake Center in downtown to the northwest corner of Ann Arbor. We assume that the trips made on Route 13 will be served by this AV service. We will estimate the ridership (i.e., demand for the service) in a more general way using the steps proposed earlier. For this example, we will use census tracts, rather than TAZ, and trip production rates directly in person trips unlike the output of the WATS trip generation model which provides trip generation information in P/A pairs.

Service area

Route 13 goes through census tracts- 4007, 4032, 4031. The area of these census tracts is approximately 4 mi^2. If we use the standard acceptable walking distance to a bus stop of ¼ mile, and make ½ mile band centered along the route length (1/4 mile on each side), we get 3.75 mi^2 as a service area (does not include transfers or getting to bus stop by some other mode). So for the purposes of further analysis, let's consider the census tracts 2007, 4032, and 4031 as the service area of route 13. There are other bus routes in these census tracts, so all transit trips for these census tracts cannot be attributed to Route 13. This will be considered later.

Trips generated

Using trip census information for the number of households in the census tracts and trip rates from southeast Michigan as reported in the 2009 MI Travel Counts Household Travel Survey (MDOT, 2010), we can estimate the number of trips (trip is defined as one-way journey between an origin and destination) generated by the population of the three census tracts overall, for trip purposes, by time of day.[1]

Table 10: Trip generation for study area

Census tracts	House holds	Trips/ day	Home-based-work trips/day	Home-based school trips/day	Home-based other trips/day	Non Home-based other trips/day
4007	1,330	10,281	1,401	718	4,655	3,232
4032	1,447	11,185	1,621	781	5,065	3,516
4031	591	4,568	662	319	2,069	1,436
Total	3,369	26,042	3,773	1,818	1,179	8,184

The non-home-based trips do not start or end at home and may start outside the service-area, so they will not be included in further analysis. Table 11 shows the distribution of trips in southeast Michigan by time-of-day, which is applied to the home-based trips in the study area (Table 12).

Table 11: Distribution of trips by time-of-day

Time-of-Day Period	Hours	Portion of Trips
Morning Peak	0601 - 0900	20%
Base	0901 - 1500	35%
Afternoon Peak	1501 - 1800	27%
Evening	1801 - 2100	13%
Night	2101 - 0600	4%

Source: MI Travel counts, MDOT, 2010

[1] MI Travel Counts average household trip rate is 7.73 trips per day, of which 1.12 are home based (HB) work trips, 0.54 are HB school trips, 3.50 are HB other and 2.43 are non HB other

Table 12: Distribution of home-based trips in study area by time period

Census tract	Home-based trips	AM Peak	Base	PM peak	Evening	Night
4007	7,049	1,410	2,467	1,903	916	282
4032	7,669	1,534	2684	2,071	997	307
4031	3,132	626	1,096	846	407	125
Total	17,850	3,570	6,247	4,820	2,320	714

The Washtenaw Area Transportation Study (WATS) gives the following modal proportions for the work trip for people who live and work in Washtenaw County as:

71% drive alone,
8% car pool,
5% use public transportation,
2% bicycle,
the rest use alternate transport or work at home.

We assume that 5% of the trips from and into our area when there is transit service are by transit. Route 13 service does not start at 6 am (closer to 7 am) and ends just before 9 pm. We will ignore this and proceed as if the buses run from 6 am to 9 pm.

Table 13: Transit ridership by time period in study area

Census tracts	Transit AM Peak	Transit Base	Transit PM Peak	Transit Evening
4007	71	123	95	49
4032	77	134	104	50
4031	31	55	42	20
Total	129	312	241	119

However, there are other bus routes in each census tract. Census tract 4031 has 2 (Routes 13 and 18), 4032 has 3 (Routes 12, 18, 3) and 4007 has 15 in the Blake Transit Center. We assume that the ridership is equally divided by the number of available routes and apply it to the transit ridership in each census track to get the ridership on Route 13 (Table 14).

Table 14: Route 13 Ridership by time period

Census tracts	AM Peak (3 hours)	Base (6 hours)	PM peak (3 hours)	Evening 3 hours
4007	5	8	6	3
4032	26	45	35	17
4031	16	28	21	10
Total	47	81	62	30

Dividing by the number of hours in each time period gives us the hourly ridership on Route 13 by time of day (Table 15).

Table 15: Route 13 Ridership/hr. (both directions) by time period

Census tracts	AM Peak	Base	PM peak	Evening
4007	1.7	1.3	2	1
4032	8.7	7.5	11.7	5.7
4031	5.3	4.6	7	3.3
Total	15.7	13.5	20.7	10

Thus, based on this estimation, the AV service would have to accommodate 16 person trips/hour from 6-9 am, 14 person trips/hour between 9am and 3 pm, 21 person trips/hr. between 3 and 6 pm and 10 person trips/hour from 6-9 pm.

4.2 Analysis of Vehicle Options

AV Powertrain Design

For this case study, four different powertrain configurations (series hybrid, parallel hybrid, conventional, and electric) were designed for Route 13 to illustrate the importance of tailoring the powertrain design for the given application to maximize the economic and environmental sustainability of the vehicle.

All powertrains were designed to operate on the drive cycle data collected from the Route 13 bus route and to be able to pass a set of performance constraints shown Table 16.

Table 16: Performance Requirements for the Route 13 Vehicle

Acceleration #1	0-16: 4.5s
Acceleration #2	11.5-26: 4s
Acceleration #3	0-30: 9.5s
Gradeability	2° at 10 mph

The drive cycle data that was used for Route 13 was obtained by driving a passenger vehicle on the actual route of Route 13 at different times of day and different days in order to help capture the effect of different traffic patterns. A Garmin GPSMAP 64S was used to record the speed data. However, as the two full Route 13 cycles shown in Figure 8 illustrate, no significant difference was observed in the drive cycles due to different traffic conditions, because most of the drive cycle corresponds to residential neighborhoods without congestion.

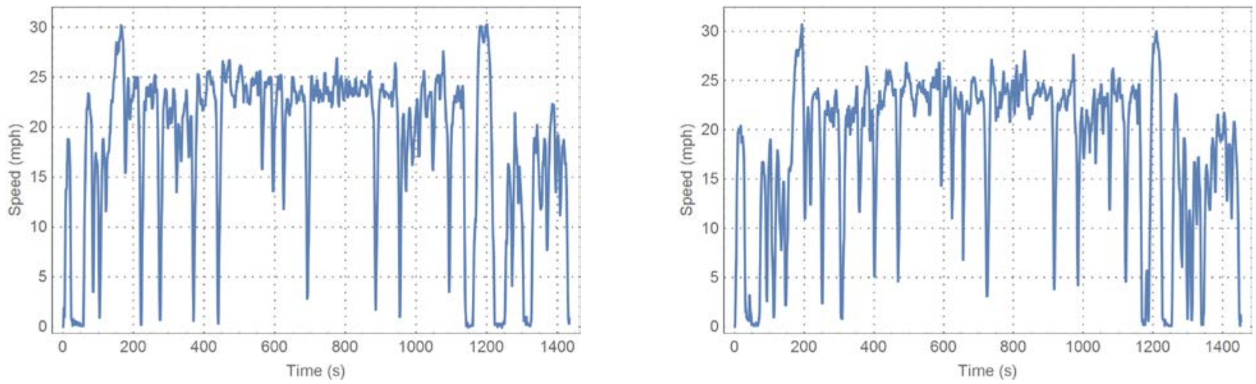

Figure 8: Data collected from two Route 13 Drive Cycles at different times of day

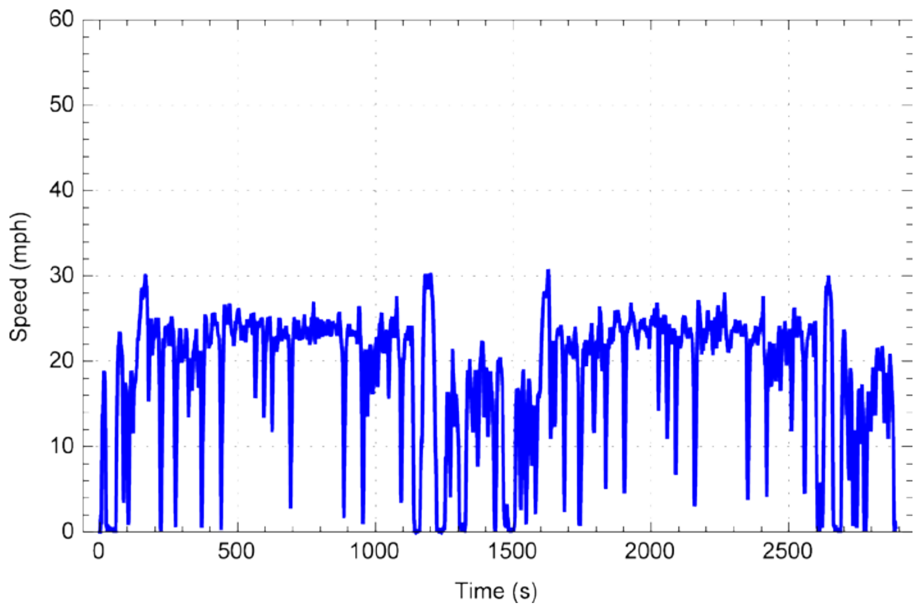

Figure 9: Concatenated data from two Route 13 Drive Cycles

In order to ensure that the vehicles, particularly the electric vehicle, will be able to operate for an entire working day of 8 hours, all of the vehicles were imposed to complete the cycle shown in Figure 9 10 times, which is a concatenation of the drive cycles shown in Figure 8. To benchmark these designs, a similar procedure was performed by optimizing all four powertrains to complete a combined UDDS and HWFET cycle 10 times (Figure 10) and satisfy a set of performance constraints (Table 17) tailored towards a typical passenger vehicle. Some of the basic vehicle parameters that were selected to be constant for all of the vehicles are shown below in Table 18. The cargo mass is selected so that these vehicles are capable of carrying four 75 kg passengers and 50 kg of luggage. The final total vehicle mass depends on the components that make up each powertrain configuration.

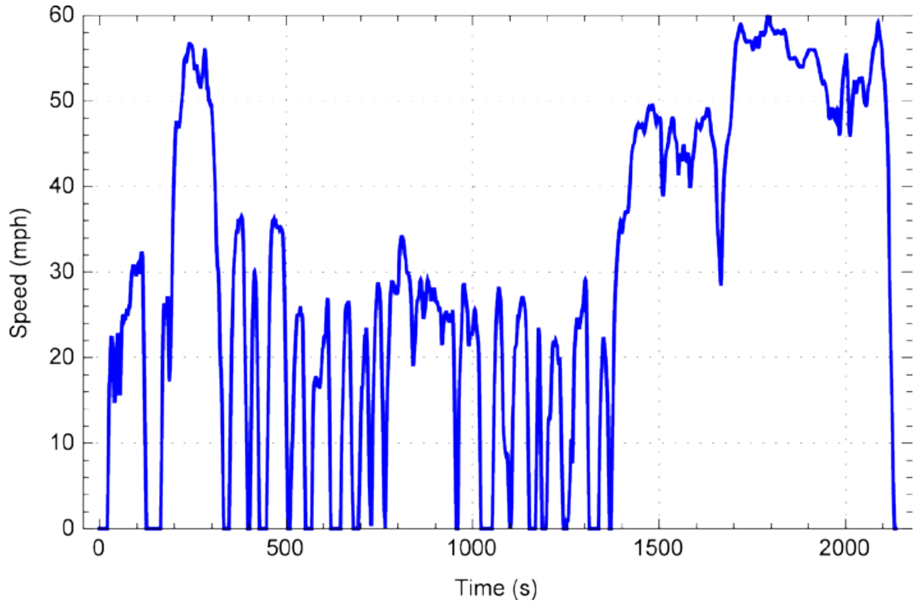

Figure 10: Combined UDDS and HWFET Drive Cycles

Table 17: Performance Requirements for the UDDS and HWFET Vehicle

Acceleration #1	0-60: 12 s
Acceleration #2	40-60: 5.4 s
Acceleration #3	0-85: 23.8 s
Gradeability	5° at 55 mph

Table 18: Constant Vehicle Parameters

Parameters	**Values**
Rolling resistance coefficient, f_{rr}	0.009
Aerodynamic drag coefficient, C_d	0.335
Wheel radius, r_w	0.282 m
Frontal area, A_f	2 m^2
Carrying capacity	350 kg

In this study, NREL's ADVISOR software (Brooker et al. 2003, Wipke et al. 1999) was used due to its large amount of empirical data and its wide use by the research community for studying powertrain design problems (Burke et al. 2009). The optimization algorithm that was chosen for this study is called DIRECT (Dividing RECTangles). This derivative-free global optimizer was chosen because the response surface for both fuel and emissions are non-differentiable. It also has been shown to perform well compared to other algorithms in this context (Gao and Porandla 2005). Unfortunately, the objective function is not Lipschitz continuous, so convergence cannot be guaranteed using DIRECT. Thus, in order to avoid convergence issues and allow for a fair comparison of the different powertrains, 1000 evaluations are allowed of the objective function for each vehicle.

The following subsections of the report present individual discussions of the optimizations for each vehicle powertrain on for both sets driving cycles and performance requirements. Then general implications of these results are discussed.

Conventional Powertrain

The conventional powertrain architecture that was utilized is shown in Figure 11 and the design variables that were optimized for the conventional architecture are listed and described in Table 19. As the starting point of the optimizations, nominal design variables were selected that ensured that all of the constraints were satisfied and that both the UDDS & HWFET and the Route 13 cycles were able to be completed. The MPG and emissions (HC, CO, and NOx) on each drive cycle is shown in Table 20 for the nominal parameters. In terms of both emissions and fuel economy, the nominal vehicle performs much better when operating on the UDDS & HWFET cycle.

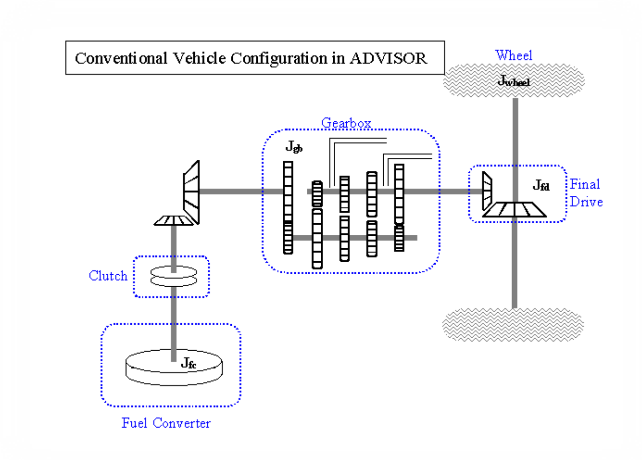

Figure 11: Conventional Powertrain Architecture (Brooker et al. 2003)

Table 19: Design Variables for Conventional Vehicle

Design Variable	**Description**
fc_trq_scale	Scaling factor for engine torque
fc_spd_scale	Scaling factor for engine speed
fd_ratio	Final drive ratio

Table 20: Performance of the Nominal Conventional Vehicle

	UDDS & HWFET	**Route 13**
MPG	25.6	19.8
HC (g/mile)	0.300	0.423
CO (g/mile)	0.805	1.08
NOx (g/mile)	0.302	0.392

For the conventional vehicle optimizations, the objective (shown in Eqn. (1)) is to reduce emissions and increase fuel economy. In Eqn. (1), the parameters a, b, c, and d are weights on the respective objectives.

$$\boldsymbol{J = -a * MPG + b * CO + c * HC + d * NOx} \qquad (1)$$

Table 21 and Table 22 show the performances of the vehicles in terms of MPG and emissions after the optimization of the powertrain. Table 21 is for the vehicle that is optimized for the UDDS & HWFET drive cycle, and Table 22 is for the vehicle optimized for the Route 13 drive cycle. In both tables the first column is the performance for the drive cycle for which the powertrain is optimized and the second column is the performance for the other drive cycle.

Table I: Performance of Conventional Vehicle Designed for UDDS & HWFET

	UDDS & HWFET	**Route 13**
MPG	27.9	20.4
HC (g/mile)	0.269	0.358
CO (g/mile)	0.739	1.15
NOx (g/mile)	0.282	0.334

Table 22: Performance of Conventional Vehicle Designed for Route 13

	Route 13	**UDDS & HWFET**
MPG	28.5	33.3
HC (g/mile)	0.232	0.179
CO (g/mile)	1.20	1.05
NOx (g/mile)	0.336	0.354

The results show that in both cases the optimization improves the performance when compared to the nominal case, as expected. More importantly, the vehicle designed for Route 13 achieves 40% better MPG and produces 35% less HC on Route 13 than the vehicle designed for the UDDS & HWFET cycle, with only a 4% increase in CO and almost the same NOx emissions.

On the UDDS & HWFET cycle, the vehicle designed for Route 13 achieves 19% better MPG and produces 33% less HC than the vehicle designed for the UDDS & HWFET cycle, but produces 42% more CO and 26% more NOx. The fact that the vehicle designed for the UDDS & HWFET cycle does not outperform the vehicle designed for Route 13 in all metrics is likely due to the fact that the vehicle designed for the UDDS & HWFET cycle must also satisfy the more stringent performance requirements shown in Table 23, while the vehicle designed for Route 13 has less stringent performance requirements shown in Table 24. These tables show the resulting constraint values for both vehicle designs. It can be seen that the performance constraints are almost all active, thus reducing these constraints will result in better objective function values. Additionally, for a more complete comparison, in the right column of Table VIII and Table 24, the vehicles designed for the UDDS & HWFET and Route 13 cycles were tested using the Route 13 and UDDS & HWFET performance constraints, respectively. This comparison demonstrates that the vehicle designed for Route 13 would actually be an infeasible design for the UDDS & HWFET optimization, because acceleration times are much higher than the required values (also note that “fail” means that the test was not even able to be performed). Finally, in Table 25, the masses of the nominal conventional and the optimized conventional designs for the UDDS & HWFET and Route 13 cycles are listed, where it can be seen that the Route 13 design is 10-12% lighter than the other vehicles.

Table 23: UDDS & HWFET Constraint Results for Conventional Vehicle

Performance Requirements		**Design for UDDS & HWFET**	**Design for Route 13**
Acceleration #1	0-60: 12 s	11.9 s	29.7 s
Acceleration #2	40-60: 5.4 s	5.07 s	17 s
Acceleration #3	0-85: 23.8 s	23.8 s	fail
Gradeability	5° at 55 mph	pass	pass

Table 24: Route 13 Constraint Results for Conventional Vehicle

Performance Requirements		**Designed for Route 13**	**Designed for UDDS & HWFET**
Acceleration #1	0-16: 4.5 s	3.39 s	2.66 s
Acceleration #2	11.5-26: 4 s	4 s	2.03 s
Acceleration #3	0-30: 9.5 s	8.06 s	4.57 s
Gradeability	2° at 10 mph	pass	pass

Table 25: Total Vehicle Mass for Conventional Vehicle

	Total Vehicle Mass (kg)
Before Optimization	1325
UDDS & HWFET	1302
Route 13	1166

Electric Powertrain

The electric powertrain architecture that was utilized is shown in Figure 12 and the design variables that were optimized for the electric architecture are listed and described in Table 26.

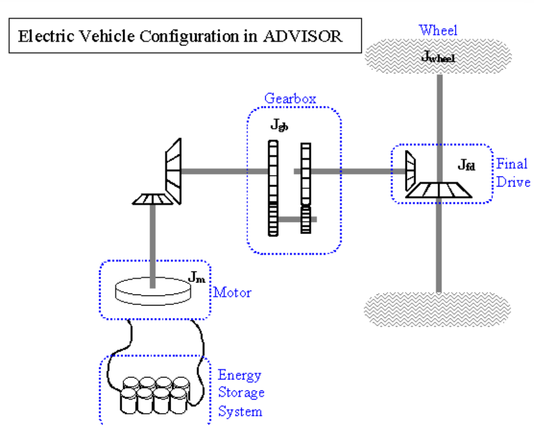

Figure 12: Electric powertrain architecture utilized (Brooker et al. 2003)

Table 26: Electric Vehicle Design Variables

Design Variable	Description
mc_trq_scale	Scaling factor for motor torque
mc_spd_scale	Scaling factor for motor speed
ess_module_num	Number of battery modules in a pack (series)
ess_cap_scale	Scaling factor for battery capacity
fd_ratio	Final drive ratio

As the starting point of the optimizations, nominal design variables were selected that ensured that all of the constraints were satisfied and that both the UDDS & HWFET and the Route 13 cycles were able to be completed. The miles per gallon gasoline equivalent (MPGGE) on each drive cycle is shown in Table 27. The nominal vehicle performs 22% better when operating on the UDDS & HWFET cycle. For the electric powertrain optimizations, the objective is simply to maximize MPGGE.

Table II: Performance of the Nominal Electric Vehicle

	UDDS & HWFET	Route 13
MPGGE	80.9	66.5

Table 28 and Table 29 show the MPGGE performances for both optimized designs on both drive cycles. The left columns show the performance on the drive cycle for which the vehicle was optimized, and the right columns show the performance on the other drive cycle. The optimizations improve the performance when compared to the nominal case, as expected. Furthermore, the vehicle designed for the UDDS & HWFET cycle performs 4% better on the UDDS & HWFET cycle than the vehicle designed for the Route 13 cycle. Similarly, the vehicle designed for the Route 13 cycle performs 5% better when operating on the Route 13 cycle than the vehicle designed for the UDDS & HWFET cycle. These results demonstrate that better MPGGE can be attained when a vehicle is optimized for its intended use.

Table 28: Electric Vehicle Designed for UDDS & HWFET

	UDDS & HWFET	Route 13
MPGGE	87.1	72.7

Table 29: Electric Vehicle Designed for Route 13

	Route 13	UDDS & HWFET
MPGGE	76.4	84.0

Table 30 and Table 31 summarize the performance constraints for the UDDS & HWFET and Route 13 cycles and to what extent the optimized designs meet these criteria. For both vehicles, on the drive cycles for which they are optimized, it can be seen that none of these constraints are active. This is likely due to the fact that the large electric motors used in these vehicles produce the most torque at lower speed, which results in a vehicle with superior acceleration performance. In the right column of Table 30 and Table 31, the vehicles designed for the UDDS & HWFET and Route 13 cycles are tested using the Route 13 and UDDS & HWFET performance constraints, respectively. Note that the vehicle designed for the Route 13 drive cycle cannot complete the UDDS & HWFET performance tests.

Table 30: UDDS & HWFET Constraints Results for Electric Vehicle

Performance Requirements		**Design for UDDS & HWFET**	**Design for Route 13**
Acceleration #1	0-60: 12 s	9.42 s	fail
Acceleration #2	40-60: 5.4 s	4.32 s	fail
Acceleration #3	0-85: 23.8 s	18.3 s	fail
Gradeability	5° at 55 mph	pass	fail

Table 31: Route 13 Constraints Results for Electric Vehicle

Performance Requirements		**Design for Route 13**	**Design for UDDS & HWFET**
Acceleration #1	0-16: 4.5 s	2.92 s	1.93
Acceleration #2	11.5-26: 4 s	3.35 s	1.73
Acceleration #3	0-30: 9.5 s	6.8 s	3.64
Gradeability	2° at 10 mph	pass	pass

Finally, in Table 32, the masses of the nominal electric vehicle and the electric vehicles designed for the UDDS & HWFET and Route 13 cycles are listed. Because the electric vehicle is designed to be able to operate for 8 hours on a single charge on both of these cycles, a large number of battery modules are needed, which increases the vehicle mass significantly.

Table 32: Total Vehicle Mass for EV

	Total Vehicle Mass (kg)
Before Optimization	2218
UDDS & HWFET	1991
Route 13	2027

Series Hybrid Powertrain

The series hybrid powertrain architecture that was utilized is shown in Figure 13 and the design variables that were optimized for the series architecture are listed and described in Table 33. The series vehicle uses a series power follower control strategy that is described in detail in Brooker et al. (2003). The control parameters for this strategy are listed and described in Table 34 and were all subject to optimization.

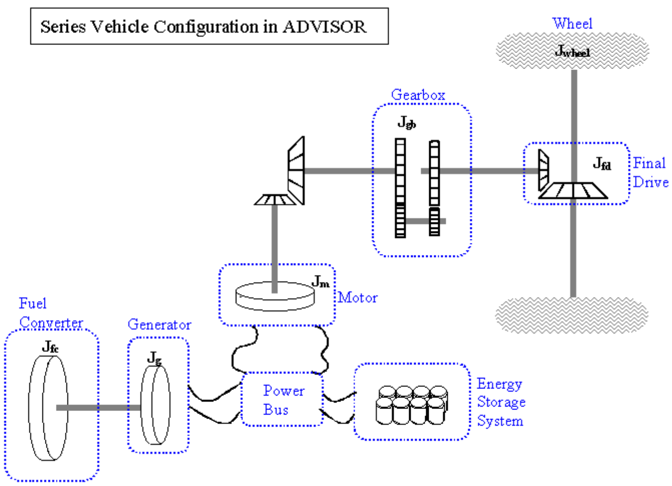

Figure 13: Series Powertrain Architecture (Brooker et al. 2003)

Table 33: Design Parameters for Series Vehicle

Design Variable	Description
fc_trq_scale	Scaling factor for engine torque
fc_spd_scale	Scaling factor for engine speed
mc_trq_scale	Scaling factor for motor torque
ess_module_num	Number of battery modules in a pack (series)
gc_trq_scale	Scaling factor for generator torque
fd_ratio	Final drive ratio

Table 34: Control Parameters for Series Vehicle

Design Variable	Description
cs_charge_pwr	SOC stabilizing adjustment
cs_min_pwr	min power command to engine
cs_max_pwr	max power command to engine
cs_max_pwr_rise_rate	fastest engine can increase power
cs_max_pwr_fall_rate	fastest engine can decrease power
cs_min_off_time	shortest period of time engine can be off
cs_fc_init_state	1=engine initially off; 0 = engine initially on

As the starting point of the optimizations, nominal design variables were selected that ensured that all of the constraints were satisfied and that both the UDDS & HWFET and the Route 13 cycles were able to be completed. The MPG and emissions (HC, CO, and NOx) of the nominal vehicle on each drive cycle is shown in Table 35. In terms of both emissions and fuel economy, the nominal vehicle performs better when operating on the UDDS & HWFET cycle.

Table 35: Performance of Nominal Series Vehicle

	UDDS & HWFET	Route 13
MPG	26.8	22.1
HC (g/mile)	0.263	0.333
CO (g/mile)	0.946	1.34
NOx (g/mile)	0.584	0.765

For the series optimizations, the objective function is the same as the conventional vehicle (shown in Eqn. (1)). In addition to the performance constraints, the series vehicle is also required to be charge sustaining; i.e., at the end of the drive cycle, the state of the charge of the battery must be at the same level as the beginning of the drive cycle.

Table 36 and Table 37 show the fuel economy and emission performances for both optimized designs on both drive cycles. The left columns show the performances on the drive cycle for which the vehicle was optimized, and the right columns show the performances on the other drive cycle. The vehicle designed for Route 13 attains better MPG and emissions on Route 13 than the vehicle designed for the UDDS & HWFET cycle. On the UDDS & HWFET cycle, it seemingly also performs better than the vehicle designed for the UDDS & HWFET cycle; however note that it actually does not meet all the performance constraints for the UDDS & HWFET use case in Table 38.

Table 38 and Table 39 summarize the performance constraints of the vehicles designed for the UDDS & HWFET and Route 13 cycles, respectively. For the UDDS & HWFET optimization, there are two active constraints that if relaxed will allow the objective function values a chance to improve.

Table 36: Series Vehicle Designed for UDDS & HWFET

	UDDS & HWFET	Route 13
MPG	30.4	25.1
HC (g/mile)	0.218	0.275
CO (g/mile)	0.565	0.760
NOx (g/mile)	0.369	0.475

Table 37: Series Vehicle Designed For Route 13

	Route 13	UDDS & HWFET
MPG	27.6	33.4
HC (g/mile)	0.234	0.196
CO (g/mile)	0.613	0.527
NOx (g/mile)	0.401	0.334

Table 38: UDDS & HWFET Constraints Results for Series Vehicle

Performance Requirements		Design for UDDS & HWFET	Design for Route 13
Acceleration #1	0-60: 12 s	10.9 s	30.4 s
Acceleration #2	40-60: 5.4 s	5.38 s	19.5 s
Acceleration #3	0-85: 23.8 s	23.8	fail
Gradeability	5° at 55 mph	pass	pass

Table 39: Route 13 Constraints Results for Series Vehicle

Performance Requirements		Design for Route 13	Design for UDDS & HWFET
Acceleration #1	0-16: 4.5 s	2.11 s	1.93 s
Acceleration #2	11.5-26: 4 s	3.31 s	1.81 s
Acceleration #3	0-30: 9.5 s	6.07 s	3.77 s
Gradeability	2° at 10 mph	pass	pass

Finally, in Table 40, the masses of the nominal series and the series vehicles designed for the UDDS & HWFET and Route 13 cycles are listed. Once again, the vehicle designed for Route 13 is the lightest.

Table 40: Total Vehicle Mass for Series Vehicle

	Total Vehicle Mass (kg)
Before Optimization	1587
UDDS & HWFET	1619
Route 13	1305

Parallel Hybrid Powertrain

The parallel hybrid powertrain architecture that was utilized is shown in Figure 14 and the design variables that were optimized for the parallel architecture are listed and described in Table 41. The parallel vehicle uses an electric assist control strategy that is described in detail in Brooker et al. (2003). The control parameters for this strategy are listed and described in Table 42 and were all optimized.

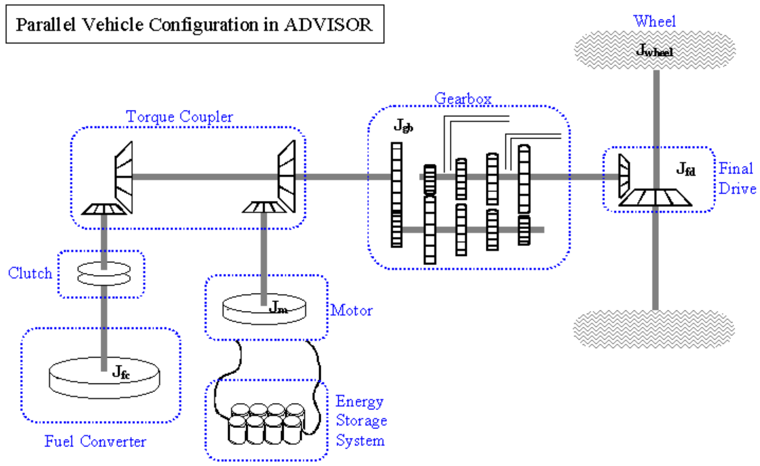

Figure 14: Parallel Vehicle Architecture used (Brooker et al. 2003)

Table 41: Design Parameters used for Parallel Vehicle

Design Variable	Description
fc_trq_scale	Scaling factor for engine torque
mc_trq_scale	Scaling factor for engine speed
ess_module_num	Number of battery modules in a pack (series)
fd_ratio	Final drive ratio
ess_cap_scale	Scaling factor for battery capacity

Table 42: Control Parameters used for Parallel Vehicle

Variable name	Description
cs_charge_trq	load on engine to charge battery pack
cs_min_trq_frac	point at which motor acts as generator
cs_off_trq_frac	min torque below which engine shuts off
cs_electric_launch_spd_lo	engine off below this speed
cs_electric_launch_spd_hi	engine on above this speed
cs_charge_deplete_bool	1=charge sustaining, 0 = charge depleting

As the starting point of the optimizations, nominal design variables were selected that ensured that all of the constraints were satisfied and that both the UDDS & HWFET and the Route 13 cycles were able to be completed. The MPG and emissions (HC, CO, and NOx) on each drive cycle is shown in Table 43.

Table 44: Nominal Parallel Vehicle

	UDDS & HWFET	Route 13
MPG	30.4197	21.2215
HC (g/mile)	0.207	0.3153
CO (g/mile)	2.2196	3.6507
NOx (g/mile)	0.2961	0.3609

For the parallel vehicle optimizations, the objective function is the same as the conventional vehicle (shown in Eqn. (1)). In addition to the performance constraints, the parallel vehicle is also required to be charge sustaining.

Table 45 and Table 46 show the fuel economy and emission performances for both optimized designs on both drive cycles. The left columns show the performances on the drive cycle for which the vehicle was optimized, and the right columns show the performances on the other drive cycle. The vehicle designed for Route 13 achieves 9% better MPG and produces 18% less HC and 21% less NOx, but 97% more CO on Route 13 than the vehicle designed for the UDDS & HWFET cycle.

Table 45: Parallel Vehicle Designed for UDDS & HWFET

	UDDS & HWFET	Route 13
MPG	31.7	21.8
HC (g/mile)	0.233	0.343
CO (g/mile)	0.739	0.945
NOx (g/mile)	0.351	0.489

Table 46: Parallel Vehicle Designed for Route 13

	Route 13	UDDS & HWFET
MPG	23.7	26.8
HC (g/mile)	0.281	0.217
CO (g/mile)	1.862	1.289
NOx (g/mile)	0.387	0.495

There are several active constraints in the second column from the right in Table 47, which, if relaxed, could lead to better performance. In Table 48, the constraints are inactive and are not holding back the Route 13 design. In the right column of Table 47 and Table 48, the vehicles designed for the UDDS & HWFET and Route 13 cycles were tested using the Route 13 and UDDS & HWFET performance constraints, respectively. It is noticed that the vehicle designed for Route 13 is not able to meet the performance requirements set for the UDDS & HWFET use case.

Table 47: UDDS & HWFET Constraints Results for Parallel

Performance Requirements		Design for UDDS & HWFET	Design for Route 13
Acceleration #1	0-60: 12 s	11.5 s	15.0 s
Acceleration #2	40-60: 5.4 s	5.37 s	6.86 s
Acceleration #3	0-85: 23.8 s	22.8 s	fail
Gradeability	5° at 55 mph	pass	pass

Table 48: Route 13 Constraints Results for Parallel

Performance Requirements		**Design for Route 13**	**Design for UDDS & HWFET**
Acceleration #1	0-16: 4.5 s	3.31 s	2.37 s
Acceleration #2	11.5-26: 4 s	2.99 s	1.57 s
Acceleration #3	0-30: 9.5 s	5.71 s	4.28 s
Gradeability	2° at 10 mph	pass	pass

Finally, in Table 49, the masses of the nominal series and the parallel vehicles designed for the UDDS & HWFET and Route 13 cycles are listed. The vehicle designed for Route 13 is lighter than the vehicle optimized for the UDDS & HWFET cycle, but increased the mass of the nominal design.

Table 49: Total Vehicle Mass for Parallel

	Total Vehicle Mass (kg)
Before Optimization	1212
UDDS & HWFET	1287
Route 13	1251

Discussion

Four vehicle powertrain architectures have been optimized for the Route 13 cycle, namely, conventional, electric, series hybrid, and parallel hybrid. The powertrains have also been optimized for a combined UDDS & HWFET cycle to benchmark vehicles that represent a typical city and highway driving use case. The results are summarized in Figure 15 and show that when the vehicle is specifically tailored for the Route 13, better fuel economy and emission performance can be achieved in general compared to a vehicle that is optimized for conventional use. Specifically, 5-40% improvement in MPG or MPGGE can be achieved with a design tailored for Route 13. HC can be improved by 15-35%. Improvements in NOx can be by up to 21%. CO emissions may be improved by 19% as illustrated with the series hybrid powertrain, but may also be compromised by up to 97% in the parallel hybrid case. This comparison demonstrates the importance of tailoring the vehicle powertrain design to the specific use case. Taking a typical vehicle that is designed for a generic city and highway use and employing it for an application such as Route 13 with low speed demands is not expected to yield the most sustainable solution in terms of fuel economy and emissions. Tailoring the vehicle powertrain to Route 13 enables proper sizing of the prime movers and gear ratios and, in the case of hybrid powertrains, proper adjustment of the powertrain control parameters according to the intended use, thereby increasing its sustainability.

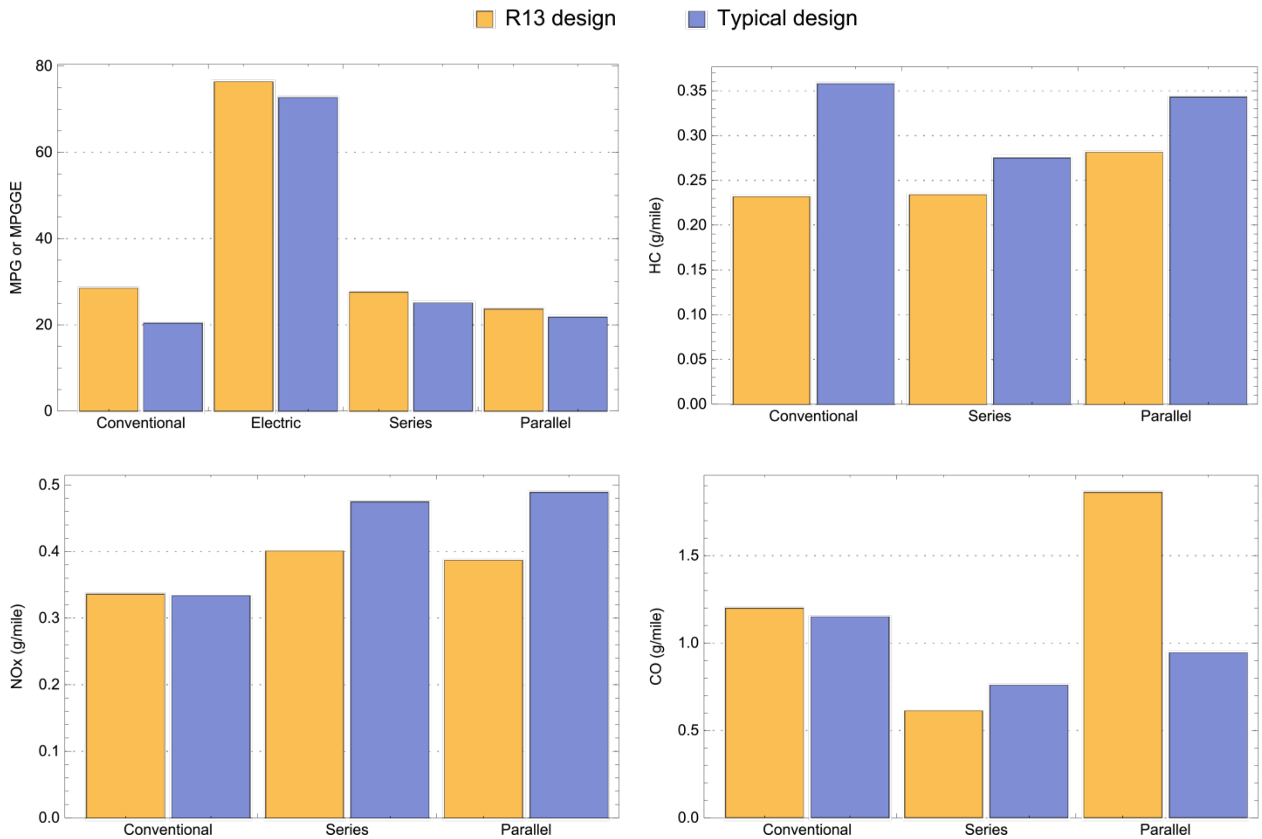

Figure 15: Comparison of fuel economy and emissions on the Route 13 between the typical vehicle and the vehicle tailored for Route 13

It is worth noting that when it comes to the hybrid architectures, the powertrain control strategy plays a significant role in determining the sustainability performance. In this case study, the default powertrain control strategies implemented in ADVISOR were utilized, which do not necessarily represent the best possible control strategies. The performance numbers are expected to change if alternative control strategies are considered; however, the main conclusion that better performance can be achieved if the vehicle is tailored for the specific application is expected to hold.

Among the powertrain architectures that involve an internal combustion engine, it is interesting to note that even though the hybrid architectures yield better mpg in the design for the UDDS & HWFET cycle as expected, the conventional architecture performs better in all aspects except for CO emissions when the vehicles are designed specifically for Route 13. This is likely due to the fact that the fairly steady operation of the vehicle at 25 mph provides the opportunity to operate a downsized engine at its sweet spot most of the time. This reduces the benefits of hybridization similar to when driving a hybrid vehicle on the highway. In addition, with the conventional powertrain the vehicle weighs up to 11% less, lowering the energy demand. Even though this performance result is dependent on the control strategies employed in the hybrid architectures as mentioned above, it is still useful to highlight that finding the best powertrain architecture is not a trivial task and analyses as illustrated in this case study are needed to make the best decision.

The electric vehicle does not produce emissions while driving; however, there may be emissions generated during charging depending on the source of electricity. The optimizations carried out in this case study did not take those emissions into account.

The electric vehicle naturally achieves a much higher MPGGE than the other designs. However, that does not readily imply that it is the best choice. Specifically, the vehicles were designed to operate for 8 hours on a single charge in this case study to be able to complete 20 full cycles of Route 13. After 8 hours, the vehicle needs to be charged, during which time it will not be available for service. Providing a continuous service would thus require the acquisition of a larger number of vehicles, i.e., increasing the size of the fleet when compared to the other powertrain alternatives. This could incur very significant acquisition costs, not only because electric powertrains cost more than conventional and hybrid powertrains due to their large battery size, but more importantly, the sensors that enable autonomy are very expensive. With LIDAR sensors costing as much as $70k and differential GPS sensors $20k, the cost for each electric EV could exceed $100k. Thus, the low operating costs of an all-electric fleet may be offset with a high acquisition cost. A solution that allows for fast battery swapping could avoid costly off-time while the vehicle charges.

4.3 Sustainability Assessment

Scope and Data

As this case study provides an example of how to apply the mobility assessment framework, we include a limited sustainability performance analysis to provide high-level recommendations for the proposed AV deployment based on key environmental metrics. Performing a quantitative analysis for each metric included in the framework requires data that could not be accessed and modeled within the timeframe of this study. However, in applying the framework we can qualitatively predict how other metrics compare between the base case and deployment scenarios. The environmental performance metrics we chose to compare for this case are the energy consumed and global warming potential (CO_2 equivalent) of the transportation systems. We consider fuel and electricity production and the vehicle production, manufacturing, and use phases of vehicle life cycles, excluding disposal. Fuel cycle data for liquid fuels and electricity are obtained from GREET (Argonne National Laboratory 2016). Vehicle manufacturing energy and emissions factors for both the bus and the AV are derived from the GREET2 vehicle cycle Excel model.

Modeling Methods

Use-phase metrics are calculated over 12 years' operation, the typical lifespan of a transit bus. Using the results of the powertrain design previously described, we chose to model both ICEV and EV powertrains to examine the AV options. Given the average low ridership estimated between 10 and 21 trips/hour, we assumed that two AV sedans provide sufficient rider capacity. As our demand estimation proved to be slightly greater than the ~12 trips/hour estimated by AAATA, we can justify the modeled AV fleet size. Using data from GREET, we calculated the energy consumed and the mass of carbon dioxide equivalent emitted from one day's operation. On a weekday, the Route 13 bus completes a 7.459 mile loop from Blake Transit Center to Rudolf Steiner Lower School and back 20 times. Weekend operation consists of 10 loop iterations on Saturdays only. Given that TheRide uses a 90% diesel, 10% biodiesel fuel blend

(BD10), data for this blend was obtained using weighted averages of the diesel, BD20, and BD100 data provided in GREET. We used the Well-to-Wheel (WTW) method, which includes the extraction, processing, and delivery of the fuel, as well as its use in the vehicle for propulsion. By selecting the proper fuel and vehicle type, GREET provides energy and emissions intensities for the total fuel cycle. To ensure that the use phase of the fuels is representative of TheRide's existing fleet and the AVs, we edited the vehicles in GREET to have the appropriate fuel economies and region-specific electricity source. We used the resulting per-mile energy and GHG-100 (kgCO_2 equivalent) factors and multiplied by the daily distance traveled by each mode scenario to find each mode's respective environmental impacts. These energy and emissions values were then scaled up according the route's weekly schedule to the 12-year typical lifetime of a transit bus.

To these values, we can add vehicle manufacturing for the bus and AVs to obtain their total life cycle impacts. The vehicle life cycle impacts were calculated using energy and emissions factors obtained in the GREET2 Excel model. These factors depend on vehicle type and powertrain configuration, on a per-vehicle-mass basis. GREET2 does not provide vehicle life cycle data for buses, therefore energy and emissions factors were interpreted from the SUV vehicle-type as advised by an Argonne National Laboratory employee (Kelly 2016). The vehicle mass for each AV mode was calculated in the design process, and for the bus modes was obtained from the manufacturer, Gillig. These masses were then multiplied by the aforementioned impact factors to arrive at the energy and emissions from producing, manufacturing, and disposing of the vehicles. This rough method yields more reasonable results than alternatives such as EIO-LCA found in Chester and Horvath (2009), as the EIO-LCA uses a cost-based, rather than materials-based, approach. Further, the impacts in the manufacturing stage of the life cycle are much less relevant when compared to the use-phase, as seen in the results.

Results

As typical in on-road transportation modes, the use-phase energy and emissions dominates the total life cycle impact, accounting for over 90% of energy consumption for all modes. Life cycle emissions are distributed very similarly to the use phase, with the exception that the hybrid bus manufacturing accounted for the greatest non-use-phase impact of 10.5%.

Use phase impacts among modes are predominantly driven by the total energy required to propel the vehicle, which is inherently a function of the vehicle mass. As the curb weight for transit buses is approximately an order of magnitude greater than conventional vehicles, significant sustainability improvements due to fuel savings result from simply downsizing the vehicle from a heavy-duty transit bus to light-duty conventional vehicle. These energy and emissions reductions from deploying smaller vehicles are realized as well when multiple vehicles are a required during periods of greater travel demand. Upwards of four ICEV sedans can theoretically provide the same level of service as a hybrid bus with less emissions, as seen in Figure 16. This multi-vehicle approach to providing transit service may lead to other benefits in terms of fleet flexibility, where vehicles may serve different routes throughout a day based on where travel demand is distributed.

Electrification of powertrains yields further energy savings from more efficient energy conversion processes across the fuel cycle. The slight increase in fuel economy from a hybrid bus saves 40,000 GJ over the 12-year life cycle of the bus. Combining an electric powertrain with downsized vehicles results in the largest energy and emissions savings, as shown in Figures 17 and 18 below. Concerns for sufficient vehicle capacity can be addressed with four electric autonomous vehicles, while still producing less impact than the current hybrid bus service. It is important to note that the environmental performance of an EV fleet is dependent on the fuel composition used to produce electricity. Although Michigan's NERC region (RFC-M) is more carbon intensive than the national average, a fleet powered by grid-connected electricity is still preferable to fossil-based liquid fuels (US EPA 2015). The emissions savings from an EV fleet would be even greater if the fleet were operated in a region with a higher penetration of renewable and nuclear generation, such as CAMX (California) or NEWE (New England).

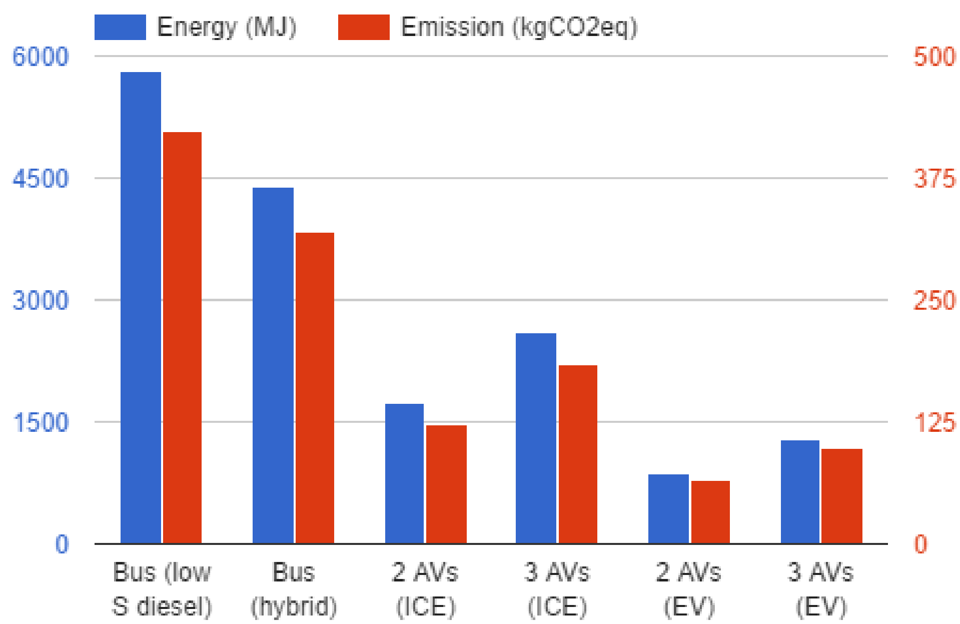

Figure 16: Well-to-Wheel Energy and Emissions for one weekday Route 13 service across various modes

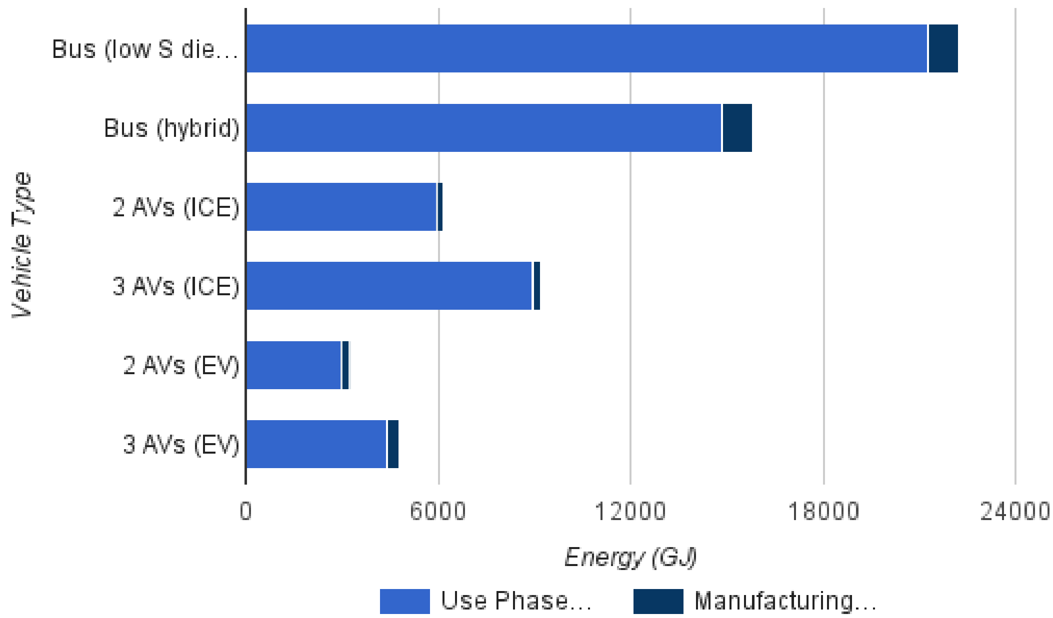

Figure 17: Route 13 Life Cycle Energy Consumption for Various Modes

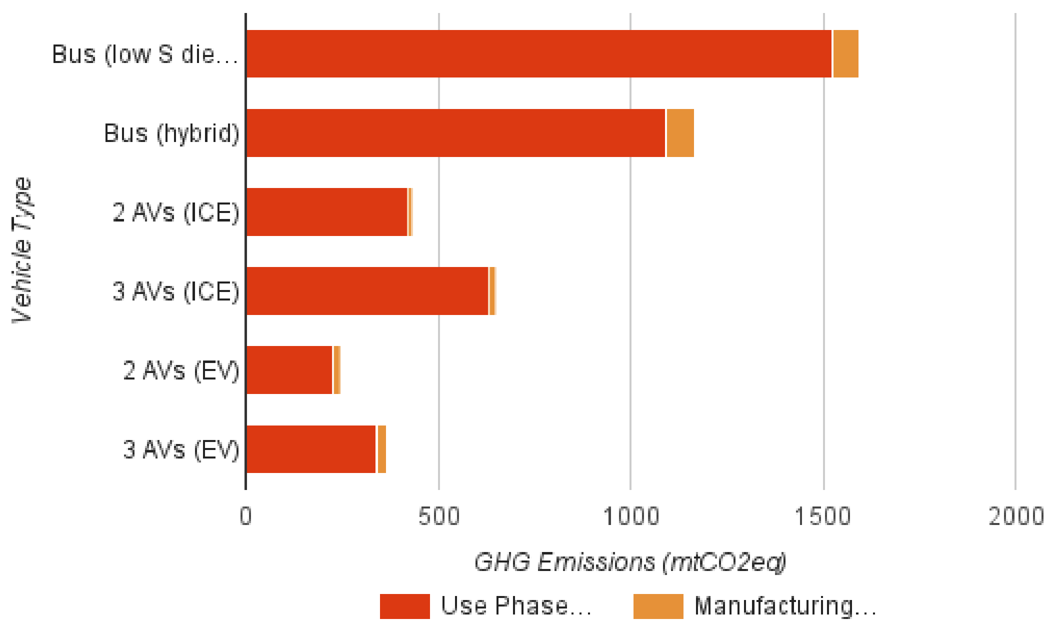

Figure 18: Route 13 Life Cycle GHG Emissions for Various Modes

Discussion

Route 13 daily service requires traveling approximately 150 miles, so there are concerns regarding range if the AV is an EV. Currently only the Tesla Model S is capable of travelling such a distance on a single charge, though forthcoming EVs (Chevy Bolt, 2017 Nissan Leaf, Tesla Model 3) aim to meet a 200-mile capability (Voelcker 2016). If travel demand is sufficiently low enough for one EV to serve from the morning throughout non-peak hours, service could be split with a second EV that charges after the morning peak and serves the tail end of the schedule. Battery swapping could alleviate range concerns as well, however no such programs have operated with great success (although battery swapping among a privately-owned, homogenous fleet may be more executable).With the reduced propulsion requirements resulting from city operation, electric powertrains can easily be designed to serve a whole day on one charge cycle.

Considerations for the cost of an AV fleet certainly is a critical factor for deciding if such a fleet should be deployed. Removing the driver will reduce operating costs by the amount of wages and benefits, however these savings must be balanced against the price of automation technologies. It is fair to assume the cost of an EV fleet will be greater than an ICEV fleet, with vehicle automation increasing those costs substantially. However, there is great uncertainty in estimating the costs for AVs as the various sensing and computing technologies that enable vehicle automation (LIDAR, cameras, etc.) are continually developing and reaching economies of scale. Purchasing a new AV fleet, like any other new fleet in transit, will be capital intensive, but may recoup any capital cost increase from operational savings in fuel and labor. Predicting these savings depends on volatile fuel prices, as well as revenue from ridership, which could increase from this new service. Fully assessing cost-effectiveness will involve a much more robust financial analysis than was conducted here.

Depending on the operations and size of an AV fleet, waiting times for service could decrease significantly. With multiple vehicles distributed throughout the route, vehicles could arrive at stops more frequently. If service is demand-responsive, wait times could be reduced while minimizing empty vehicle miles traveled and unnecessary emissions. However, the specific operational rules of such a service must be defined in order to determine various benefits and costs of an on-demand service. Such rules would include where the vehicles are stationed before/after serving a ride, if or how often relocation of AVs is required, or if AVs can serve other nearby routes when not needed for their original service. In order to understand the implications of these varying types of service, system-level simulations like agent-based modeling need to be explored.

4. Key Findings

In assessing the best strategies for deploying AVs within Ann Arbor, it is essential that a systems-based approach is used to understand the multidimensional impacts potentially brought about by this disruptive technology. Considerations for AV deployment must span beyond the vehicle's own impacts, including how AV systems will affect travel demand, other new and existing modes, user's behavioral choices, and the environments in which the AVs operate. We score these systems according to sustainability and system performance metrics to understand their potential benefits and limitations. Although trade-offs must be considered in deciding how an AV system is designed and operated, understanding a wide range of impacts, at least at a qualitative level, is important for recognizing unintended consequences or avoiding otherwise ignored risks.

Both supply and demand elements of an AV system must be examined to determine if there is a strong business case. In the case of Route 13, low ridership yields low utilization on a capital-intensive asset. Adjusting the mode supplying transit service according to demand will result in higher return on investment and a more self-sustaining business. Alternatively, novel transit modes can be introduced that provide a new service or support existing modes (e.g., last-mile) that may tap into latent demand for travel. With automated driving and connectivity among vehicles, new business models will arise, and it is important that we remain open-minded to these unforeseen opportunities in order to fully realize the potential benefits brought about by AVs.

Shared Rides, Fleets over Personal, Private AV travel

In choosing candidate services for initial deployment, many characteristics must be evaluated to determine whether a candidate is preferable or not. For instance, if AVs are privately owned personal vehicles, we can predict a net increase in energy consumption as the result of more convenient travel and longer tolerable commutes. Even greater miles traveled occur when AVs can search for parking far away from the owner's destination, or in the worst case, return to the owner's home between trips. When no incentive is provided to encourage sharing rides, personal AV deployment does little to remove vehicles from the road or reduce miles travelled. Currently platforms exist to connect drivers travelling to and from similar locations such as RideWith (by Google-owned Waze), however these ridesharing platforms are still in early stages of development with limited penetration.

Matching Supply and Demand

When considering replacing public transit buses with AVs, providing sufficient capacity is an obvious concern, for which low-ridership routes offer the most feasible case. In this scenario, climate-related benefits do not result from the automation of the vehicle, but simply by improving the vehicle's operating efficiency through down-sizing and electrification. Self-driving capability does facilitate the usage of downsized fleets, by replacing the driver with additional room for riders; an effect more impactful on smaller vehicles with less capacity. We can predict the benefits from this type of deployment, as seen in the results of the Route 13 case study, and make inferences on other related scenarios. For example, if ridership is so small that no constant demand for a route ever exists, it would be best to replace the bus service with a strictly demand-responsive AV system. With higher ridership routes, on-demand service is unnecessary as there is a relatively constant flow of demand.

Candidates for AV Deployment

Throughout the course of this project, we considered various types of transportation services that could be provided by shared AV fleets. After creating our analysis framework and applying it to the case study of TheRide's Route 13, we performed a similar, albeit less robust, assessment of other deployment opportunities and arrived at high-level recommendations for these candidates, as in seen in Table 50 below.

Table 50: Opportunities and Recommendations for AV Deployment

Service	Pros	Cons	Recommendation
Amtrak	Inc. transit ridership Less parking need	Taxi, Uber competition	For low ridership (on-demand)
Bioresearch/ UM-VA	Operations energy	Assistance needs AAATA competition	On-demand
Bus Route	Op. energy, comfort wait time	Range req./fueling Larger fleet, more VMT	For low ridership (on-demand)
Intra-zone	Op. energy if shared Reduced need for parking	Difficult to share Taxi, Uber competition	Yes
Last mile	Wait time, Inc transit	Difficult to share	Yes
Night Owl	Op. energy, wait time	Security, Sensing challenge	No
North-Central	High load factor	Already served well Congestion	No
Park & Ride	Inc. transit ridership Wait time	Taxi, Uber competition Low opportunity to share	Yes (off-peak)
Senior	Access	May need assistance	Yes (able-enough)

As mentioned previously, these candidates must be assessed on a case-by-case basis and individually assessed with the analysis framework to provide a comprehensive understanding of how these systems could enhance transportation sustainability within Ann Arbor. Although some services may be similar in function, nuances engrained in the context of the service can be critical to its viability. For example, average ridership for two particular routes may be quite similar, however understanding demand frequency and peaks can help guide decisions toward the specific capacity (sizing of vehicles and fleets) as well as whether an on-demand service is appropriate. Performing some level of quantitative analysis on candidate services and routes can provide insights when deciding between different candidates, however results are limited by both data availability and the specific design of systems being considered.

Qualitative characteristics of potential services can be used to decide on the candidates most appropriate for initial deployment. Other details of the service affect its viability, such as the type of user of the service. In the cases of a senior shuttle service or an inter-hospital route, an AV fleet may exclude potential riders who are less able-bodied and may require an attending driver. For near-term deployment, service schedules should be limited to daylight due to sensing difficulties at night, along with clearly defined thresholds for optical conditions determining when AVs can and cannot safely operate.

Geographic Scope and Deployment Progression

Deploying AVs on public roadways should occur in a controlled manner within environments that they are prepared for and that can safely accommodate unmanned vehicles. When AVs move outside of designated testing centers such as Mcity, permissible roadways must be explicitly defined and enforced. Limiting deployment to within the city boundaries of Ann Arbor reduces risk due to high-speed travel and permits greater control over traffic laws and enforcement as the city can define the extent of allowable AV travel. Figure 19 shows our suggested progression of AV deployment onto public roads. Initially it is most appropriate to confine AV travel to one or a few constrained routes to serve as proofs-of-concept for real-world AV operation. A progressive deployment of AV systems allows for earlier penetration of AVs on roadways, as simpler systems have lower technical and legal barriers to overcome compared to more expansive and flexible transportation services. Initially selecting services that operate in low-pedestrian environments reduces risk and difficulty in AV navigation. Limiting AVs to a specific route allows robust mapping data to be gathered to ensure precise navigation. As on-board sensing, computing, and control systems advance, AVs can effectively operate in more complex environments. From serving single origin-destination trips, deployment can then be expanded to confined areas where any origin/destination can be served as long as the AV remains in the permitted area. This sort of service could occur within a shopping or downtown center, or at events such as concerts or sports games, where demand analysis shows high intra-zonal flows.

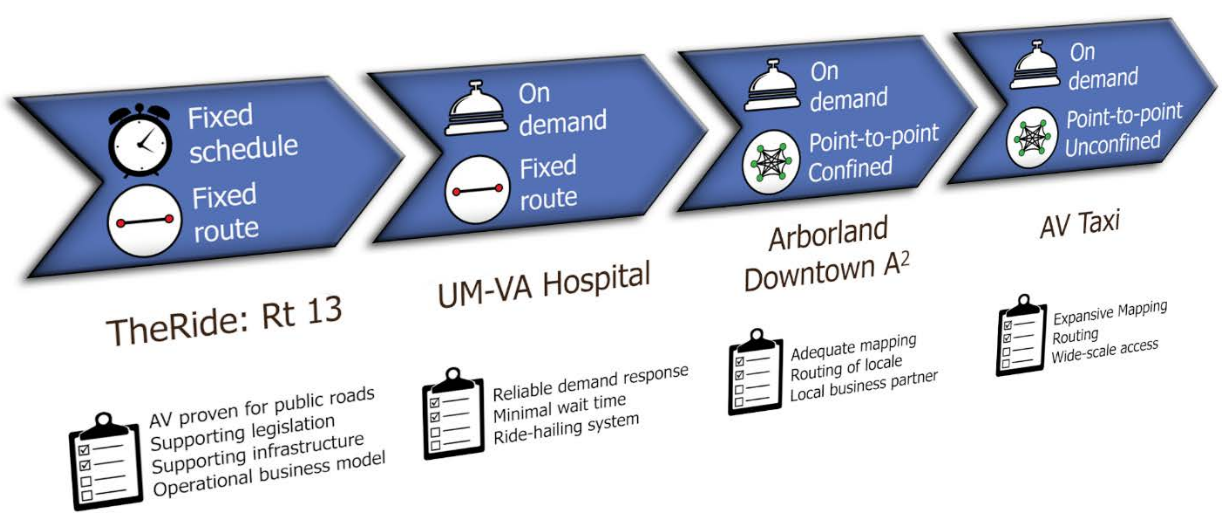

Figure 19: Progression of AV systems, example of service and requirements

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CENTER FOR SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

School of Natural Resources & Environment, 440 Church Street, 3012 Dana Building, Ann Arbor, MI 48109-1041
734-764-1412 | css.snre.umich.edu