Shared Autonomous Taxis: Implementing an Efficient Alternative to Automobile Dependency

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Submitted in partial fulfillment of the requirements for the degree of Bachelor of Science and Engineering
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Abstract

Societal dependence on the automobile has been steadily growing since its creation. Despite safety hazards, rising oil prices, environmental concerns, and increasing congestion, today’s transportation system is dominated by privately owned cars. The problem is that no alternative mode of transportation exists that can compete with the level of convenience provided by the private automobile. Fortunately, the emerging technology of autonomous vehicles has made possible the implementation, within preexisting infrastructure, of a new transportation system that could finally break the automobile addiction. A Shared Autonomous Taxi system would provide the same level of convenience as the privately owned automobile and would take advantage of autonomous car technology and the concept of ridesharing to address all of the major issues associated with automobile dependency: energy consumption, environmental health, traffic congestion, and safety. Its comprehensive benefits and straightforward implementation make a Shared Autonomous Taxi system an ideal alternative to the current automobile-dominant transportation system.
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Chapter One
Introduction
The ultimate goal of transportation systems is to get people from point A to point B in the most effective way possible. This is complicated by the overwhelming number of factors that impact what makes a form of transportation the most effective: speed, reliability, comfort, safety, flexibility, convenience, cost and environmental impact to name a few. The automobile satisfies most of these conditions—especially in terms of speed, reliability, comfort, and convenience—and people’s desire for these benefits seems to outweigh the negative consequences associated with the automobile. Societal preference for the automobile is illustrated by the following chart which shows that the personal vehicle has come out on top as the primary mode of transportation for all trips taken throughout the day.

![Figure 1.1](RITA Bureau of Transportation Statistics 2001)

Furthermore, it is apparent that the automobile is the primary mode of transportation to work in most parts of the United States; the New York City metropolitan area is the only notable exception. Below are recent statistics for principle means of transportation to work in the United States as a whole (2008), Mercer County, New Jersey (2010), and New York City, New York (2012):
Table 1.1 (U.S. Department of Transportation 2010, Onboard Informatics 2010, FindTheData 2012)

<table>
<thead>
<tr>
<th>Mode</th>
<th>United States</th>
<th>Mercer County, NJ</th>
<th>New York City, NY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total #</td>
<td>Percentage</td>
<td>Total #</td>
</tr>
<tr>
<td>All Workers</td>
<td>143,996,000</td>
<td>100</td>
<td>163,253</td>
</tr>
<tr>
<td>Total Automobile</td>
<td>124,177,000</td>
<td>86.2</td>
<td>137,680</td>
</tr>
<tr>
<td>Drive Self</td>
<td>108,776,000</td>
<td>75.5</td>
<td>119,742</td>
</tr>
<tr>
<td>Carpool</td>
<td>15,402,000</td>
<td>10.7</td>
<td>17,938</td>
</tr>
<tr>
<td>Public Transportation</td>
<td>7,170,000</td>
<td>5.0</td>
<td>10,979</td>
</tr>
<tr>
<td>Walk</td>
<td>4,061,000</td>
<td>2.8</td>
<td>7,349</td>
</tr>
<tr>
<td>Taxi, Motorcycle, Bike or Other</td>
<td>2,690,000</td>
<td>1.8</td>
<td>2,084</td>
</tr>
<tr>
<td>Work at Home</td>
<td>5,897,000</td>
<td>4.1</td>
<td>5,161</td>
</tr>
</tbody>
</table>

The speed, reliability, comfort and convenience of the automobile have perpetuated its position as the preferred mode of transportation, intensifying societal automobile dependency despite consequential issues of environmental impact, traffic congestion and safety. Based on these statistics it is clear that for most people the pros of personal automobile use outweigh the cons, at least in comparison to the existing alternatives. This is further evidenced by increasing numbers of vehicle miles travelled (VMT) and car ownership. There has been a 34% increase in travel by light-duty vehicles (consisting of passenger cars, pickup trucks, minivans and SUVs) from 1990 to 2003 and “VMT has grown more than twice as fast as population, with economic, social, and land use factors spurring increased vehicle trip making and VMT per person” (U.S. Environmental Protection Agency 2006). Simultaneously, car ownership of personal vehicles has increased: the percentage of households owning no motor vehicle has decreased from 20.6% in 1969 to 9.2% in 1990 and to 7.9% in 2001. Also by 2001, 8.5% of households owned more than three vehicles—more than the proportion that owned none (U.S. Environmental Protection Agency 2006). As dependency on the automobile continues to increase, its negative effects also increase both in actual magnitude and in public awareness of their impact. This pattern will continue until a viable and realistic alternative that is convenient enough to compete with personal automobile use exists. The focus of the research for this thesis is to study the impact and consequences of today’s dominant mode of transportation, the privately owned, human-operated
automobile, and to explore alternative modes of transportation that could provide society with a safer and overall more efficient transportation system that reduces environmental impact and congestion. The limitations of current alternative transportation systems will be addressed, and the emerging technology of autonomous vehicles will be discussed in light of its potential to overcome these limitations. Finally, a Shared Autonomous Taxi system, which takes advantage of this new technology to provide a viable alternative to the current conventional automobile-based transportation system, will be proposed as the future of safe, efficient and environmentally sound transportation.

1.1 Environmental Impact

One of the biggest issues associated with automobile dependency is the high level of energy consumption and consequential environmental impact. The following diagram illustrates total energy consumption by source and sector (in quadrillion BTUs, and by percentage) in the United States in 2010.

*Figure 1.2 (U.S. Energy Information Administration 2011)*
This image illustrates the high level of energy consumption within the transportation sector: 27.4 quadrillion BTU, or 28% of all U.S. energy consumption in 2010 (U.S. Energy Information Administration 2011). It also reflects the automobile’s high energy consumption as it is the dominant mode within the transportation sector. Specifically, personal road transportation (including passenger vehicles, other automobiles, and motorcycles) accounted for 17,000 trillion BTU of energy consumption in the United States in 2007—far more than any other mode in the transportation sector (U.S. Department of Transportation 2010). Furthermore, the preceding diagram illustrates that 71% of all petroleum use was allocated to the transportation sector. The high level of energy consumption by the transportation sector is most likely the reason that petroleum is the most used energy source in the United States, sourcing 37% of all energy consumption. In light of the energy crisis and dwindling global supply of oil, this rate of consumption is very problematic (U.S. Energy Information Administration 2011).

The high volume of energy consumption in the transportation sector also translates into a high environmental impact. The following table presents energy-related greenhouse gas emissions (in million metric tons of carbon dioxide) by end-use sector from 2004-2009:

<table>
<thead>
<tr>
<th></th>
<th>Residential</th>
<th>Commercial</th>
<th>Industrial</th>
<th>Transportation</th>
<th>Total²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>1,228</td>
<td>1,054</td>
<td>1,731</td>
<td>1,962</td>
<td>5,975</td>
</tr>
<tr>
<td>2005</td>
<td>1,261</td>
<td>1,069</td>
<td>1,675</td>
<td>1,991</td>
<td>5,996</td>
</tr>
<tr>
<td>2006</td>
<td>1,192</td>
<td>1,043</td>
<td>1,661</td>
<td>2,022</td>
<td>5,918</td>
</tr>
<tr>
<td>2007</td>
<td>1,242</td>
<td>1,079</td>
<td>1,662</td>
<td>2,040</td>
<td>6,022</td>
</tr>
<tr>
<td>2008</td>
<td>1,228</td>
<td>1,073</td>
<td>1,597</td>
<td>1,938</td>
<td>5,836</td>
</tr>
<tr>
<td>2009</td>
<td>1,167</td>
<td>1,019</td>
<td>1,385</td>
<td>1,857</td>
<td>5,428</td>
</tr>
</tbody>
</table>

Table 1.2 (RITA Bureau of National Transportation Statistics 2010)
In 2009, the transportation sector was responsible for 34.2%, or approximately one-third, of all carbon dioxide emissions in the United States (RITA Bureau of National Transportation Statistics 2010). The fuel combustion process that powers the automobile also produces other greenhouse gases and hazardous pollutants including but not limited to hydrocarbons, carbon monoxide, nitrous oxides, volatile organic compounds and particulate matter. Transportation accounted for about 27% of all greenhouse gas emissions in the United States in 2008. Furthermore, the transportation sector is the largest end-use source of carbon dioxide and the level of emissions shows no sign of decreasing or even plateauing. Transportation sources are the fastest growing greenhouse gas emission source in the United States and account for a staggering 47% of the total increase in U.S. emissions since 1990 (U.S. Environmental Protection Agency 2012). The following chart plots the evolution of greenhouse gas emissions by end-use economic sector from 1990 to 2003.

![Figure 1.3 (U.S. Environmental Protection Agency 2006)](image)

Upon breaking down the emissions of the transportation sector by source, it appears that vehicles used for personal transit (passenger cars and light trucks which include SUVs, minivans and pickup trucks) are the worst perpetrators, accounting for
62% of all greenhouse gas emissions within the transportation sector (U.S. Environmental Protection Agency 2006). The following pie chart breaks down the greenhouse gas emissions by source in the transportation sector of the United States in 2003.

![Pie Chart](image)

**Figure 1.4 (U.S. Environmental Protection Agency 2006)**

From 1990 to 2003 there was a 19% increase in greenhouse gas emissions by the light duty vehicle group which consists of passenger cars and light trucks. This can most likely be attributed to the 34% increase in vehicle miles travelled (VMT) by said vehicles over the same period which heavily outweighs the small improvements that have been made in terms of fuel economy (U.S. Environmental Protection Agency 2006). This steadily increasing VMT and subsequent increase in emissions is a serious hazard to environmental health.

It could be said that some effort has been made to decrease the energy consumption and environmental impact of automobiles through the development of electric cars and hybrids. However as illustrated by the 2010 Transportation Statistics Annual Report below showing total sales in thousands of cars per year, the proportion of
hybrid vehicles sold is too low to have any significant effect on reducing the environmental impact of automobiles.

<table>
<thead>
<tr>
<th>Year</th>
<th>Domestic Hybrids (thousands of cars/yr)</th>
<th>Imported Hybrids (thousands of cars/yr)</th>
<th>Total hybrid sales (thousands of cars/yr)</th>
<th>Total vehicle sales (thousands of cars/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>3</td>
<td>81</td>
<td>84</td>
<td>17,299</td>
</tr>
<tr>
<td>2005</td>
<td>16</td>
<td>190</td>
<td>206</td>
<td>17,445</td>
</tr>
<tr>
<td>2006</td>
<td>24</td>
<td>229</td>
<td>254</td>
<td>17,049</td>
</tr>
<tr>
<td>2007</td>
<td>78</td>
<td>275</td>
<td>353</td>
<td>16,460</td>
</tr>
<tr>
<td>2008</td>
<td>86</td>
<td>230</td>
<td>316</td>
<td>13,493</td>
</tr>
<tr>
<td>2009</td>
<td>82</td>
<td>208</td>
<td>290</td>
<td>10,601</td>
</tr>
</tbody>
</table>

Table 1.3 (RITA Bureau of Transportation Statistics 2010)

Furthermore, while hybrid and electric vehicles may help reduce emissions and the corresponding environmental impact of the automobile industry, they do nothing to improve roadway safety or to ease the increasing traffic congestion associated with automobile dependency.

1.2 Safety

Safety is a very important and often overlooked issue associated with automobile use. It is estimated that the number of worldwide injuries from traffic-related accidents ranges anywhere from 20 million to 50 million each year (Folsom 2011). Based on this statistic, traffic injuries are projected to become the third highest cause of global disease and injury by 2020. And not only is the automobile increasingly becoming one of the leading causes of injury, it is also a leading cause of death. In 2002, 1.18 million people worldwide died from traffic-related crashes, comprising 2.1% of all deaths and placing traffic incidents at 11th among the leading causes of death. In the United States alone, in 2006, there were 43,664 deaths due to motor vehicle traffic-related injuries compared to
30,896 deaths due to firearm injuries and 17,034 homicides. Furthermore, the 2,575,000 total traffic-related injuries resulted in an estimated economic cost of $230 billion. In 2007, the United States saw 37,248 fatal crashes resulting in 41,059 deaths. As if these numbers are not staggering enough on their own, they become all the more shocking when put in a comparative perspective. “For 2003-2007, deaths in California traffic alone exceeded American deaths in the Iraq war in each of four age groups between 18 and 50. For the 20th century, 667,701 American troops have died at war and 3,070,325 Americans have died on our roads” (Folsom 2011). The amount of publicity related to casualties in the war in Iraq is shocking compared to apparent public acceptance of deaths from automobile accidents. It underscores how blinded society is to the danger of driving (Folsom 2011).

The following map displays all traffic related deaths from 2001 to 2009 across the United States. Each dot represents one fatality color coded as follows: blue represents a pedestrian, green a cyclist, orange a motorcyclist, and purple a vehicle occupant. With an estimated 12.3 traffic fatalities per 100,000 inhabitants of the United States per year, it comes as no surprise that the dots on the map below are hardly distinguishable because there are so many (Snyder 2011).
The reason that automobiles are so dangerous is that they rely completely on human control and vigilance. When absorbed in the routine of driving every day with no complications it is easy to forget how unpredictable and unreliable humans are. The level of vigilance that a driver maintains while driving is inconsistent, making the roads unsafe. Driver vigilance can be impaired by something as innocent as lack of focus, drowsiness, or going into ‘autopilot’ but it can also be attributed to driving under circumstances of impaired ability which happens tragically often. In 2006 alcohol was involved in 41% of all fatal crashes in the United States, and 1.46 million arrests were made of drivers under the influence of alcohol or narcotics (Folsom 2011). Whether it is a conscious choice to drive under the influence or simply the unavoidable lack of focus and vigilance in day-to-day driving, the human variable makes automobiles an extremely dangerous mode of transportation.

1.3 Congestion and Ridesharing

Another key issue spawned from automobile dependency is the increased number of vehicles on the road and the resulting increase in traffic congestion. As the automobile began its rise to dominance, the number of cars on the road doubled between 1940 and 1960 and traffic congestion has become increasingly worse ever since (Atlantic Media Group 2010). The Texas Transportation Institute studied and reported on traffic congestion trends in the United States from 1982 to 2003 and found that in 2003 there were 3.7 billion total hours of delay and 2.3 billion gallons of fuel wasted idling in traffic jams (Longley 2005). Based on this staggering number, it is clear that congestion further contributes to the issues of energy consumption and environmental impact that have been discussed. Traffic congestion is also a huge inconvenience for drivers. The TTI reports that the delay per peak period traveler per year increased from 16 hours in 1982 to 47 hours in 2003. And the impact is increasingly magnified in urban areas where congestion is becoming unbearable. The number of urban areas with over 20 hours of delay per peak traveler per year has increased from 5 in 1982 to 51 in 2003 (Longley 2005). Congestion is also very wasteful in terms of gasoline consumption. The 2010 National
Transportation Statistics reported on the amount of fuel wasted due to congestion in a variety of urban areas in 2005, and the result was an average of 120.1 million gallons in very largely populated areas, 23.4 million in large areas, 7.3 million in medium areas and 1.8 million in small areas (U.S. Department of Transportation 2010). If roadways were free of congestion, this waste could be avoided.

The causes of traffic congestion can be divided into two categories: recurring causes which consistently cause congestion and non-recurring causes which cause additional unpredictable congestion. Recurring causes, which consist of insufficient capacity, unrestrained demand, and ineffective management of capacity, are the primary reason for congestion but non-recurring causes, which include incidents, work zones, weather events, special events, and emergencies, can also contribute (U.S. Department of Transportation 2003). Therefore, recurring causes should be the main focus of efforts to reduce congestion. The bottom line is there are simply too many cars for our roadways to support. Since adding more capacity is costly, and in some condensed urban areas infeasible, the solution lies in figuring out how to reduce the number of cars on the road. One straightforward way to do that is to increase vehicle occupancy through ride-sharing. The average vehicle occupancy of a car in 2009 was 1.59; any increase in that number would reduce the number of cars on our roadways (U.S. Department of Energy 2010). Implementing a system that enables increased ride-sharing would be a logical place to start in the effort to reduce congestion.

Carpooling is one way to reduce the number of cars on the road, but unfortunately travel demand is too diffused to make this a realistic solution. The probability that two or more people who know each other and are willing to share a ride need to make a round trip from the same origin to the same destination at approximately the same time in both directions, especially on a regular basis, is extremely small. Furthermore, the fact that people only carpool with people who they know cuts down the potential rides shared. And even in a situation where carpooling with a friend, family member or coworker does work out on most days, unanticipated variations in schedule can often get in the way.

Another existing ridesharing mechanism that reduces the number of automobiles on the road is public transportation. While the ridesharing involved in public transportation is certainly the right idea and some existing systems have been successful
in unique situations like New York City, all conventional public transit efforts have been singularly unsuccessful in relieving the automobile congestion issue. Except in niche situations, the service provided by public transportation cannot compete with the automobile and as a result it goes unused for the most part except by those who don’t have access to an automobile. Public transportation provides an alternative to the automobile for some, but the majority of people still prefer driving their own automobile whether for comfort, flexibility of schedule or door-to-door service. Public transportation does not relieve enough congestion to keep up with the increasing congestion associated with increasing populations, increasing vehicle miles travelled and continuous automobile dependency in most places. Public transportation provides little to no congestion relief except in the New York City metropolitan area as evidenced by Table 1.1 which shows that 54.6% of New York City commuters use public transportation and only 28.9% drive (FindTheData 2012). In comparison, in the United States as a whole only 5% use public transportation and 86.2% drive (U.S. Department of Transportation 2010).

One existing alternative form of transportation that successfully rivals the convenience and comfort of the automobile while promoting congestion-reducing ridesharing is Personal Rapid Transit. A system of automated pod cars that run on a segregated guideway with offline stations, PRT promotes ridesharing while still providing on demand service with minimal stops. Unfortunately, though PRT technology has been around for decades and there are some small scale systems in place around the globe, it has yet to be implemented on a widespread scale as is necessary to make an impact on traffic congestion. This is primarily because of the high cost and complicated implementation of the infrastructure required for the system. Newly developing autonomous vehicle technology, which allows cars to drive themselves on existing roadways, has the potential to make this kind of system easily implementable by removing the need to build extensive infrastructure.
1.4 Autonomous Vehicles and Shared Autonomous Taxis

Autonomous vehicles have the potential to improve roadway safety and reduce congestion simply by removing the human elements of delayed reaction time and lack of concentration. But most importantly they could completely revolutionize our transportation system by allowing for the implementation of the Shared Autonomous Taxi system proposed by this thesis. In off-peak hours, autonomous taxis could function as driverless Zipcars, making car sharing just as, if not more convenient than car ownership since it removes the need to find parking. Clearly, most people prefer the convenience of travelling by automobile, and in order to do so everyone wants to have their own car. Autonomous taxis could provide people with the same level of convenience and on-demand service of the automobile, but without ownership. They would solve the biggest inconvenience associated with car sharing as it is implemented by Zipcar: the fact that the user must pick up and drop off the car in its reserved spot. Autonomous taxis would solve the problem of vehicle relocation. Say one person wants to pick up a car at point A, drive it to point B and leave it there. The next customer wants to pick up a car at point C—but there are none there. That is where the newly developing technology of autonomous vehicles comes in. The autonomous taxi could drive itself from point B to point C and serve both customers.

While autonomous taxis would make car sharing much more convenient, during the peak hours of rush hour traffic a Shared Autonomous Taxi system could really have an impact on reducing congestion. A system that can identify a traveler’s origin using GPS as they enter their destination and departure time, either at a taxi stand or through their computer or phone, could use this information to group trips and facilitate carpooling in autonomous taxis between strangers who would not otherwise share a vehicle. This brand of ridesharing is comparable to the sharing of an elevator. The requirements to make it possible are that two or more people are travelling from about the same origin to about the same destination, or simply along the same route, within an acceptable, say two minute, wait. The probability of these circumstances is significantly higher than that of the requirements for conventional carpooling. Given the similarity in origin, destination and timing of so many trips that occur during peak hours, the number
of cars on the road is truly excessive. A Shared Autonomous Taxi system would help reduce the number of cars on the road and decrease rush hour congestion. Another benefit of the system is that it would be simple to implement, especially compared to a system like Personal Rapid Transit which similarly is centered on the idea of ridesharing but is expensive and complicated to implement. A Shared Autonomous Taxi system requires no expensive infrastructure since autonomous cars can function on existing roadways. The development of the autonomous vehicle technology that makes this system possible is well underway at companies like Google and at research institutes and Universities across the globe. However, despite the progress toward autonomous vehicle technology and the possibility of an easy implementation, there are sure to be many hurdles, both legally and socially, down the road. But if these obstacles can be overcome, a Shared Autonomous Taxi system has the potential to break the automobile addiction and solve many of the issues associated with automobile dependency, completely revolutionizing the current transportation system.
Chapter Two
Review of Alternative Transportation Systems Literature
2.1 The Importance of Ride Sharing

As has been established, the key to reducing traffic congestion is ridesharing. Upon re-examining the 2008 statistics for the principle mode of transportation to work (in thousands) in the United States from Table 1.1, now focusing not just on the dominance of the automobile but on vehicle occupancy, it is clear that the vast majority of people drive alone in their own vehicle rather than engage in ridesharing either by carpool or by the use of mass transportation:

<table>
<thead>
<tr>
<th></th>
<th>Total (in thousands)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Workers</td>
<td>143,996</td>
<td>100</td>
</tr>
<tr>
<td>Total Automobile</td>
<td>124,177</td>
<td>86.2</td>
</tr>
<tr>
<td>Drive Self</td>
<td>108,776</td>
<td>75.5</td>
</tr>
<tr>
<td>Carpool</td>
<td>15,402</td>
<td>10.7</td>
</tr>
<tr>
<td>2 passengers</td>
<td>11,846</td>
<td>8.2</td>
</tr>
<tr>
<td>3 passengers</td>
<td>2,088</td>
<td>1.5</td>
</tr>
<tr>
<td>4+ passengers</td>
<td>1,467</td>
<td>1.0</td>
</tr>
<tr>
<td>Public Transportation</td>
<td>7,170</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 2.1 (U.S. Department of Transportation 2010)

Furthermore, “shared use of vehicles also has declined for other forms of personal travel, due in part to smaller household sizes and increased vehicle availability. Across all trip purposes, the average number of occupants per vehicle in 2000 was 1.6 persons, down from 1.9 in 1977” (U.S. Environmental Protection Agency 2006). These statistics illustrate the lack of carpooling in our society. With about three quarters of the working population driving one person per car to get to work, it’s no wonder rush hour traffic is so bad. The explanation for why so many people drive by themselves to work is that it is exceptionally convenient. Carpooling is difficult to organize, and public transportation is usually less convenient than driving both because it doesn’t operate door to door, and because it runs on a schedule. There simply is no existing ridesharing alternative that is quite as convenient as driving, and therefore no incentive for people not to drive.

Mark Gorton, the founder of LimeWire discusses the issue of congestion, particularly in urban areas like New York City and proposes a new form of mass transit in his essay, “Using Information Technology to Achieve a Breakthrough in
Transportation in New York City.” He points out that while traffic in New York City is abysmal, many commuters still choose to drive because they simply do not have a good alternative. But Gorton insists that “the private automobile is the single most inefficient means of moving people in a city” and that “by catering to the private automobile, we have inadvertently made an engineering choice that maximizes danger, noise, pollution, and congestion and creates a host of other problems that suck the life out of our public spaces” (Gorton 2008). He highlights the space inefficiency of the automobile with the following chart:

![How much space do we need?](Gorton 2008)

This visual shows the amount of space required to transport one passenger via a sampling of different modes of transportation. It seems clear that the individual automobile is the most space inefficient mode. However, it is important to note that the measurement for bus transportation is assumes that buses are being used efficiently by always being filled to capacity. In actuality, U.S. bus transit runs with only approximately a quarter of its seats occupied on average, and so the amount of street space required per traveler as depicted in the image above should be quadrupled (U.S. Department of Transportation 2009). Similarly, if the average car occupancy were to increase to just two, the depicted street space required per traveler would be halved. And the more passengers per car, the more efficient that mode could become.
Gorton recognizes that without issues of congestion and limited parking, the automobile certainly offers a faster transit time than any other existing mode of transportation. He aims to illustrate that building transportation systems that revolve primarily around automobile use, especially in a society where traveling one person per car is the norm, has created quite a mess in terms of traffic congestion. This makes travel by car much slower and more inefficient. Attempts to reduce congestion that focus on increasing road space rather than reducing the number of cars on the road only perpetuate congestion problems because the automobile remains the mode best served by transportation infrastructure. “The previous answer to congestion was to build more roads, bridges and tunnels,” but since this kind of development only caters to the automobile, it only results in continued driving and continued congestion. It has become increasingly clear to our society “that it is impossible to build its way out of congestion problems” (Gorton 2008).

In exploring possible solutions to the issue of congestion, Gorton uses logic from his technical background in computer science. “From a network management point of view, the road networks of New York and many other large cities are horribly engineered. The traditional traffic engineering solution to congestion problems is to try to increase capacity. However, similar problems in computer engineering are solved by reducing the underlying need for traffic” (Gorton 2008). Gorton is advocating that continuing to build more roadways and create more capacity for cars will never fix the situation as was once believed. He thinks the focus should be on developing a new transportation system that will reduce the demand for automobiles and therefore the need for increased automobile capacity.

Gorton’s proposed transit system which he coins Smart Para-transit is a new form of mass transportation that “offers trip times highly competitive with the private automobile to nearly all points in the region” and “takes advantage of the existing road network and requires very little in the way of capital investment” (Gorton 2008). The Smart Para-transit system would consist of a fleet of vehicles, varying in size, which would be routed not on a predetermined schedule or route like existing trains and buses, but on a specialized route determined by a central computer which decides how best to group requested trips at a given time. The key motivation behind the system is to “group
and optimize the existing trips that take place on the road network” (Gorton 2008). For example in many instances, especially in a dense city like New York, several people will be making very similarly routed trips in their cars at one time:

Take for example the group of people who want to travel from Tribeca to Montclair, NJ around 5:30 PM on a Tuesday. There might be a dozen people who plan to make this trip by car in a 15 minute period. These dozen people might require 8 separate cars for their trips. Instead of 8 separate cars, one large van could fit 12 people and consolidate these 8 vehicles into just one vehicle. The van could make 3 quick stops in Tribeca, pick up all 12 people and head directly to Montclair. Once in Montclair, the van could stop at a couple of central transit points, and then continue directly to some passengers houses (Gorton 2008).

Below is a visual representation of the difference this system would make if implemented on a large scale.

Figure 2.2 (Gorton 2008)
Despite the fact that New York City has an excellent public transportation system, “for outlying parts of the New York City region the transit options are a poor substitute for the mobility provided by the private car” (Gorton 2008). Furthermore, in most other cities like Los Angeles for example, where mass transit systems leave much to be desired, the dependency on automobiles and the convenience that they provide is even greater. The beauty of Smart Para-transit is that it utilizes the roadway space efficiency of carpooling and mass transit while still providing convenience and mobility comparable with that of a personal automobile. A user of Smart Para-transit could simply enter their trip information (origin, destination and time of departure) via computer or smart phone and the system’s computer would quickly determine the best trip grouping based on that information and trip information inputted by other passengers. It would then direct the user to a convenient pickup point near their current location where they would be picked up by a car, van, or bus—depending on the size of the group—within minutes. Passengers would be dropped off at a few different points, conveniently near their desired destinations. For users of Smart Para-transit, “the trip would be nearly as direct as a car trip and would involve no transfers and minimum waiting” (Gorton 2008).

Despite its near comparable convenience with the automobile, Smart Para-transit will require some initial support to become truly superior to private automobile travel. If these shared vehicles are sitting in the same traffic as private cars, and travel on less direct routes than cars, the trip time will be a bit longer. However, if more roads had HOV lanes, and Smart Para-transit vehicles had access to these lanes then they could “zip through the bridges and tunnels while private cars sat stuck in traffic” (Gorton 2008) and offer trip times far superior to the automobile which in turn would encourage more people to use the system. Gorton believes that the end result could mean a nearly congestion free road network—in fact he roughly estimates that the widespread implementation and use of Smart Para-transit in New York City would result in an 80% reduction in automobile traffic making a cleaner, quieter and more peaceful city. Mark Gorton’s Smart Para-transit could dramatically reduce congestion in dense areas like New York City, and similar concepts of organized ridesharing could be applied on a more widespread scale to reduce congestion around the globe.
2.2 Personal Rapid Transit

The automobile remains dominant in society causing continuous problems of traffic congestion and pollution because there is no viable alternative available today that matches the automobile in terms of convenience. The goal of public transportation is to provide such an alternative while promoting ridesharing among the masses in order to reduce both congestion and automobile emissions, but it falls short of achieving that goal. Despite the fact that there are some excellent mass transit systems in existence (e.g., the New York City metropolitan area) overall they have proven insufficient to substitute for the private car. As reported in the 2010 National Transportation Statistics, the 2,977,884 million total transit miles in the United States in 2008 are split between 2,973,509 million highway vehicle miles travelled and 4,375 miles of other transit (U.S. Department of Transportation 2010), and can be broken down as follows:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Highway VMT in millions</th>
<th>Percentage of total highway VMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total transit miles</td>
<td>2,977,884</td>
<td>100%</td>
</tr>
<tr>
<td>Highway, total</td>
<td>2,973,509</td>
<td>99.85%</td>
</tr>
<tr>
<td>Passenger Car</td>
<td>1,615,850</td>
<td>54.26%</td>
</tr>
<tr>
<td>Other 2-axle, 4-tire vehicle</td>
<td>1,108,603</td>
<td>37.23%</td>
</tr>
<tr>
<td>Motorcycle</td>
<td>14,484</td>
<td>0.49%</td>
</tr>
<tr>
<td>Truck</td>
<td>227,458</td>
<td>7.64%</td>
</tr>
<tr>
<td>Bus</td>
<td>7,114</td>
<td>0.24%</td>
</tr>
<tr>
<td>Other Transit</td>
<td>4,375</td>
<td>0.15%</td>
</tr>
</tbody>
</table>

Table 2.2 (U.S. Department of Transportation 2010)

Other transit, which includes other modes like light rail, heavy rail, motor bus, and trolley bus compared to highway miles travelled is only 4,375 million. Clearly passenger cars and other 2-axle, 4-tire cars are the dominant mode of transportation as they make up the vast majority of vehicle miles travelled in the United States (U.S. Department of Transportation 2010). Furthermore, as previously noted in Table 2.1, 86.2% of workers
commute to their jobs by private automobile, most of whom drive alone and do not carpool, while only a mere 5% use public transportation (U.S. Department of Transportation 2010). This again reiterates the fact that the majority of the population either does not have access to public transportation that takes them from home to work, or if they do they would prefer to take their own car. This is not too surprising given that “conventional forms of public transit require passengers to collect in groups, wait until a large vehicle with a fixed schedule arrives, and travel on a predetermined route stopping for additional passengers on the way” (Ultra Global PRT 2011). Most people choose to commute in private automobiles instead because it offers flexibility of schedule and a faster trip time. If public transportation systems could reduce passenger wait and travel times then they could potentially see a lot more use, which is the goal of Personal Rapid Transit.

A Personal Rapid Transit (PRT) system consists of small, driverless electric vehicles known as pod cars that run on a specially-built guideway and stop at offline stations to pick up and drop off passengers at their request. These systems and their many benefits have the potential to completely revolutionize the current transportation system. PRT offers the benefits of public transportation in terms of reducing traffic congestion through a ridesharing alternative to the automobile, but in a much more convenient way for the user. The system runs on demand, making wait times for passengers minimal or even nonexistent. Once the passenger is on board, it takes them directly to their destination without any stops (unless it is during peak traffic time and they are sharing the pod car with someone who has a nearby destination), making travel time comparable, or possibly even superior to the automobile since it runs on its own guideway and doesn’t have to sit in traffic. Peter Muller, the president of PRT Consulting describes it as “an automated taxi that runs on its own roadway and doesn’t have to stop” (Almasy 2011). Although the concept of Personal Rapid Transit has been around for more than 50 years, it has yet to be implemented on a large scale. There are, however, small pilot systems operating in Masdar City in the district of Abu Dhabi in the United Arab Emirates, in Uppsala, Sweden as a test track, and even at Heathrow International Airport in London, England. Below are some images of the Masdar City PRT system that are useful in visualizing how the system functions.
Figure 2.3 (Almasy 2011)

Personal rapid transit cars are designed to carry four to six people at a time.

Figure 2.4 (Almasy 2011)

When commuters need a car, they pay a fare and a car shows up within seconds at the station.
The original plan for Masdar was to have a system with multiple stops, however the project was scaled back and as of now consists of just two stops and the guideway that connects them. Nonetheless, Robbert Lohmann, the manager of marketing and sales
of 2getthere, the company that installed the system, is proud of this pilot project saying, “we’d be happy if there’s an expansion of the system in the future. If there is not, I’ll be happy to operate what we have here and show the world how unique the system is, and what the capabilities of the system are” (Vorano 2011). Their small PRT system is enough to demonstrate that “the perfect thing with this is that, unlike other systems, it operates on demand” (Vorano 2011).

Another company that has been working on the development of Personal Rapid Transit since the 1990’s is Vectus Intelligent Transport. After over a decade of research, tests and simulations Vectus decided to build a full scale test track in February 2005. Uppsala, Sweden was selected as the site for this test system because of its “availability of communications, the possibility to test in winter conditions, internationally recognized authorities for complementary approvals and university and industrial structure available” (Vectus 2011). The Swedish Railway authority approved the completed track for test runs with visitors in March 2008 and fully approved for operation with multiple vehicles and passengers in September 2008 (Vectus 2011). Below is an image of the layout:

Figure 2.7 (Vectus 2011)

The outer loop of the track runs 300 meters long with an inner station-track of 100 meters, designed to allow merging between the tracks at full speed (12.5 m/s). This configuration was “carefully selected to be as small as possible but still with the capability of proving all aspects of the full scale system” (Vectus 2011). Thus the project
has been successful in that it effectively demonstrates the Vectus PRT technology and the potential for implementation at a larger scale (Vectus 2011).

Finally, Ultra Global PRT recently launched a PRT system at Heathrow Airport in London, England that is now fully operational. The system consists of 21 pod car vehicles, 3.8 kilometers of guide way, and three stations: one at Terminal 5 and two in the T5 Business Car Park. Traffic between the Terminal and the Car Park is busy, and Ultra’s PRT system provides 800 passengers per day with transportation between the two. Before the PRT system was in place, the primary mode of transport between these two points was by bus. The system is expected to eliminate 50,000 bus journeys per year by offering a much more convenient and efficient option, reducing travel time by about ten minutes for the average passenger compared to the original bus system. The pods offer a silent, comfortable five minute ride for up to four passengers and their luggage with no wait time—the central computer distributes pods at each station to accommodate passenger demand—and a direct journey to their desired destination (Ultra Global PRT 2011). Some descriptive statistics for three months of vehicle operation are provided below, followed by images of the Heathrow pod cars, elevated guide way, offline stations, and the computer system with which passengers request rides.

<table>
<thead>
<tr>
<th></th>
<th>September 2011</th>
<th>October 2011</th>
<th>November 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours of Operation</td>
<td>646</td>
<td>667</td>
<td>647</td>
</tr>
<tr>
<td>Number of Occupied Vehicle Journeys</td>
<td>21,695</td>
<td>21,527</td>
<td>22,183</td>
</tr>
<tr>
<td>Average Wait for Vehicle</td>
<td>9.6 seconds</td>
<td>8.3 seconds</td>
<td>10.3 seconds</td>
</tr>
<tr>
<td>Percentage with Zero Wait Time</td>
<td>76%</td>
<td>86%</td>
<td>84%</td>
</tr>
<tr>
<td>Service Availability</td>
<td>98.6%</td>
<td>99.9%</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

Table 2.3 (ULtra Global PRT 2011)
The system is a success from an environmental standpoint as well. The battery powered, zero emissions pod cars use 70% less energy than it takes to power a car, and 50% less energy than a bus and they can recharge while sitting at the station waiting for passengers (ULtra Global PRT 2011).

Despite the success of these initial systems, the widespread development and use of PRT systems with comprehensive networks that would truly transform transportation is still a very distant dream. One large obstacle is that PRT systems require the construction of new infrastructure, which takes time, commitment, and a lot of money. The small system at Heathrow cost 30 million pounds to implement (including costs
associated with the initial research and development of PRT technology), equivalent to nearly 47 million dollars (Ultra Global PRT 2011). Systems that have been proposed in the United States are estimated to be even more costly. A company called Connect Ithaca submitted a proposal to the state of New York in September for a PRT system in the city of Ithaca consisting of a 9 mile track, 350 cars and 26 stations that would connect the two local colleges and other points of interest. The anticipated cost for this project is between $150 and $168 million not including design fees. Many cities cannot afford or are simply unwilling to make that large of an investment in PRT (Almasy 2011).

Another U.S. city seriously considering the implementation of a PRT system is San Jose, California. The sustainability officer for San Jose Department of Transportation Laura Stuchinsky says that they think PRT shows a lot of promise and could be very beneficial to the city, but that because it is a very new technology, they “need an evaluation that is really robust, that evaluates the readiness of the technology and the ability of the companies to deliver and really do what we need to have done” (Almasy 2011). Their concern is that “when a city orders a bus or puts in light-rail, it can look at data from other systems to know what it is getting. With PRT, there is nothing but dreams and a few test tracks” (Almasy 2011). The standing question in San Jose is whether the investment is worth that risk. Jacob Roberts of Connect Ithaca, the company behind the proposed PRT system in Ithaca, New York says “it’s a question of which U.S. city is going to be first. Who is going to have the political will to say I want this done on my watch? There aren’t a lot of communities racing to be the one to take the biggest risk” (Almasy 2011). Until someone does take the risk, there is little hope of widespread PRT development in the United States. And even when the risk is accepted, widespread development would to be a long, drawn out process due to the complex and costly nature of PRT infrastructure. This thesis will examine the new developing technology of autonomous vehicles, and explore the ways in which they may be able to overcome these limitations to the development of PRT by eliminating the need for extensive infrastructure and making possible a convenient, fast, safe and clean mode of transportation that promotes ridesharing with fairly straightforward implementation.
Chapter Three
Autonomous Vehicles
3.1 Current Development of Autonomous Vehicle Technology

The development of autonomous vehicle technology is well underway across the globe, and completely autonomous cars may be ready for roadways sooner than expected. Vehicle autonomy can be classified into three categories that help define its progress: driver assistance, full autonomy confined to a separate roadway from normal traffic, and full autonomy integrated into existing roadways and traffic (Folsom 2011). Driver assistance autonomy is already in place and can be seen among features of cars sold commercially by many automobile vendors—cruise control, collision avoidance, lane following, blind spot monitoring, and self-parking systems are all examples of driver assistance features that provide partial autonomy. If autonomy at this level can be perfected and commercialized, then why not proceed to the development of fully autonomous vehicles? As Professor Alan Woodward of the University of Surrey says, “We already have systems that park your cars for you and automatically brake—the next obvious step is to have cars take over the routine driving” (BBC 2011). And indeed full autonomy, both on the segregated level and city-ready level is well on its way as evidenced by the 2005 DARPA Grand Challenge, the 2007 DARPA Urban Challenge, and the current testing and demonstrations by those experimenting with this new technology. According to Ferdinand Dudenhoeffer, a professor of automotive economics at the University of Duisburg-Essen, “there’s a big trend for completely computer-controlled cars—many companies and research centers in several countries are working on it and it is hard to say who’s got the most-developed vehicle at the moment” (Healy 2011). Some of the major contestants include Google, the BMW project in Germany, the Italian VisLab project, Carnegie Mellon, Virginia Tech, and Princeton PAVE.

3.1.1 Google’s Automated Toyota Prius

One of the leading efforts in the race for the best autonomous vehicle technology is the project underway at Google. Google’s fleet of automated Toyota Priuses has driven over 190,000 miles total on California roads with limited human intervention. The
lead tech on the project, Chris Urmson, declares that the heart of the system is the laser range finder which can be seen in the image below, mounted on top of the modified Toyota Prius (Guizzo 2011).

![Figure 3.1 (Guizzo 2011)](image)

This Velodyne 64-beam rotating laser gathers measurements which are used to generate a comprehensive 3D map of the surrounding environment as the car drives (Guizzo 2011). The vehicle combines these laser readings with high-resolution maps in the system to create data models that allow it not only to drive itself, but to adhere to traffic laws and to avoid potential obstacles and collisions. Google’s automated car is also equipped with a handful of additional sensors including “four radars, mounted on the front and rear bumpers, that allow the car to ‘see’ far enough to be able to deal with fast traffic on freeways; a camera, positioned near the rear-view mirror, that detects traffic lights; and a GPS, inertial measurement unit, and wheel encoder, that determine the vehicle’s location and keep track of its movements” (Guizzo 2011).
With this technology, Google’s automated cars have demonstrated the ability to follow traffic regulations as well as the ability to respond to unpredictable obstacles. In one demo the car is stopped at a red light and “after the light turns green, the car starts a left turn, but there are pedestrians crossing. No problem: it yields to the pedestrians, and even to a guy who decides to cross at the last minute” (Guizzo 2011). Google has even taken the project a step beyond adhering to the rules of the road in recognizing that “sometimes, however, the car has to be more ‘aggressive.’” When going through a four-way intersection, for example, it yields to other vehicles based on road rules; but if other cars don’t reciprocate, it advances a bit to show the other drivers its intention. Without programming that kind of behavior, Urmson said, it would be impossible for the robot car to drive in the real world” (Guizzo 2011). Based on successful demonstrations such as these, it appears that a fully automated car like Google’s has the potential to be integrated into existing roadways and traffic in the near future.

In December 2011, Google was awarded a U.S. Patent for their automated car technology (BBC 2011). The patent describes and protects Google’s “methods and devices for transitioning a mixed-mode autonomous vehicle from a human driven mode to an autonomously driven mode” (Gomez 2011), specifically the process of stopping on a particular ‘landing strip’ so the vehicle can reference its exact position and obtain an autonomous vehicle instruction and thereby be able to begin operating in autonomous mode (Gomez 2011). Though this does not prevent others from inventing competing autonomous technology, it does restrict other United States companies from using the same precise methods as Google in developing an automated car.

3.1.2 The German MIG

Another autonomous vehicle project is being developed by the Artificial Intelligence Group of the Freie University of Berlin. “The autonomous car is a conventional VW Passat modified for “drive by wire”. Electronic commands from the computer are handed over directly to the accelerator, the breaks and the steering wheel of
The vehicle, named “Made in Germany” or MIG, determines its exact position using a very accurate GPS unit and a map of the city. Three laser scanners at the front, and three at the rear of the vehicle detect any car or pedestrian 360 degrees around the car. The measurements are done by emitting laser pulses in the invisible infrared region. The echo of light pulses is detected, and its flight time determines the distance to objects. A rotating laser scanner on top of the vehicle provides additional measurements—up to one million scan points per second of the 3D structure of the environment. A black and white video camera behind the rear view mirror is used to detect the white lane strips and center the car on its lane. Two color cameras are used to identify traffic lights and their state (Autonomos Labs 2011).

The group has been working on the MIG project for about four years, putting $551,800 into the car (Healy 2011). Initial testing took place at the former Tempelhof airport where the vehicle successfully navigated “an obstacle course simulating real-world conditions which included car-lanes, traffic lights, cyclists, a couple with a stroller, and a ball being suddenly thrown into the path of the MIG car” (Nippard 2010). After this success, the MIG was ready for a real test drive, and so its creators showed off their masterpiece in a demonstration on the streets of Berlin, Germany as pictured below.

![Figure 3.2 (Healy 2011)](image_url)
The demonstration was successful—the MIG navigated traffic with no need for intervention by the driver who rode along in case of emergency. Raul Rojas, the head of the University’s research group for artificial intelligence boasts that “the vehicle can recognize other cars on the road, pedestrians, buildings and trees up to 70 meters (about 71 yards) around it and even see if the traffic lights ahead are red or green and react accordingly… In fact, the car’s recognition and reaction to its environment is much faster than a human being’s reaction” (Healy 2011). Though he recognizes that there are challenges ahead in terms of legality and social acceptance, Rojas believes that automated cars like MIG are the future of transportation because of their potential to increase accessibility and mobility for those otherwise unable to drive, improve roadway safety, and reduce environmental impact both with increased efficiency and the possibility of car sharing.

3.1.3 The Autonomous Journey from Italy to China

Another autonomous vehicle project is underway at the Artificial and Intelligent systems laboratory, better known as VisLab, at the University of Parma in Italy. The vehicles that they are working with are fully electric vans manufactured by Piaggio, the maker of the Vespa scooter. Each van is equipped with seven cameras, four laser scanners, a GPS, and an inertial sensor, as well as three computers that process all of the data (Guizzo 2010).

Two cameras hanging above the windshield provide stereo vision, used for identifying lane markings and the terrain slope. Three synchronized cameras behind the windshield stitch their images into a 180-degree panoramic frontal view. The laser scanners—three mono-beam and one four-plane laser beam—detect obstacles, pedestrians, and other vehicles, as well as ditches and bumps on the road (Guizzo 2010). Once all of this data is collected, the computers on board take over. One of the computers processes all data and images collected from the front, another does the same for the sides, and the third combines all of this data in order to determine what the
vehicle’s path ought to be. Once the path is determined, the steering, acceleration, and breaking controls are programmed to follow it (Guizzo 2010). Below is an image of one of VisLab’s autonomous vehicles, driving along smoothly with no one in the driver’s seat and just one passenger in the back.

![VisLab's autonomous vehicle](image)

*Figure 3.3 (Guizzo 2010)*

After extensive testing in the laboratory setting, the VisLab engineers resolved to take their vehicle on a test drive in the real world. As the director of VisLab, Alberto Broggi noted, “When you do things in the lab, it all really works. But when you go out in a real road, with real traffic, real weather, it’s another story” (Guizzo 2010). And so, Broggi and the rest of the VisLab team decided to embark upon a 13,000 kilometer journey from Parma, Italy to Shanghai, China in order to really put their autonomous vans to the test. The intercontinental journey began in July 2010 and finished at the 2010 World Expo in China in October 2010. Due to the lack of availability of maps for the entire route particularly in Mongolia and Kazakhstan, required to plan and execute the route autonomously, the team settled on a simplified but still challenging approach that would suffice to provide extensive data concerning their vision and navigation systems. The vans were to travel in pairs, using a following method. The lead van would drive
autonomously when maps and GPS were available, but would be driven by a human for the majority of the journey. The second van would visually track the lead van and subsequently plan and execute its own route, autonomously following the leader. Despite some extenuating circumstances where a human driver took over to avoid safety hazards like other careless drivers and pedestrians or to compensate for delays, the follower vans operated autonomously an estimated 90 percent of the time (Guizzo 2010). Below is an image of the route travelled by the convoy, comprised of two of these leader-follower pairs of autonomous vans and six support trucks.

![Figure 3.4 (Guizzo 2010)](image)

Alberto Broggi emphasizes that the goal of this journey was not just to show off VisLab’s accomplishments thus far, but to stress their systems and collect data that will help them perfect their vehicles. “The idea is that after the test is over, the researchers can use the data to study every instance when things didn’t work, such as when the vehicle failed to detect lanes or misidentified an obstacle” (Guizzo 2010). And the trip has certainly been a success from that standpoint with an estimated 50 to 100 terabytes of data collected along the way. They even implemented a major upgrade during the trip when the follower van was failing to follow the lead van forcing them to make some adjustments and re-upload the software to the vans. According to Broggi, the end of the journey will just be the beginning of several new projects (Guizzo 2010).
3.1.4 Carnegie Mellon’s Distributed Car Control System

In accordance with the contemporary development of partial and full autonomy technologies for cars, researchers at Carnegie Mellon University have developed a method to test and verify the safety of these kinds of systems. Andre Platzer, an assistant professor of computer science at Carnegie Mellon and a leader in formal verification method development (including methods to verify aircraft collision avoidance systems and robotic surgery devices), is one of the main collaborators on the project. He is a big proponent of automated vehicle systems and their potential to increase driving safety and efficiency, yet he acknowledges that “it would be foolish to move to such a system, however, unless we can be certain that it won’t create problems of its own,” (Spice 2011) hence the motivation behind his research at Carnegie Mellon. He says that “the dynamics of these systems have been beyond the scope of previous formal verification techniques, but we’ve had success with a modular approach to detecting design errors in them” (Spice 2011). As Platzer points out, safety verification of autonomous vehicle systems is especially challenging because there is no one computer in control, rather a distributed system of separated vehicles making their own decisions simultaneously (Spice 2011).

Platzer and his team began by developing a model of the system in which the control systems of each car combined to make compatible decisions on acceleration, braking, lane changing and freeway entrance and exit. They broke the problem into modular pieces, starting with two cars in a single lane and expanding to multiple cars in multiple lanes simulating an actual highway. They used mathematical methods to formally verify the safety of the system and insure that the cars would not crash into each other along the way (Spice 2011). This distributed car control system “allows for the cars to talk to each other, kind of like a pack of wolves, or hive mind. If one car needs to pull off the freeway, then the other cars move to make space. If a car in front has to slow down, the other cars know—in a matter of milliseconds—that they must slow down too” (Anthony 2011). The major limitation with Carnegie Mellon’s system is that it only applies to a straight highway. In reality there is still a lot of work ahead to make this system applicable in the real world of curved roads, intersections and other variables, but the hope is that their work has the potential to be generalized and applied to more
complex systems. As Andre Platzer puts it, “Any implementation of a distributed car control system would be more complicated than the model we developed, but at least now we know that these future systems aren’t so complex that we can’t verify their safety” (Spice 2011).

3.1.5 Virginia Tech’s Odin

Team Victor Tango, the research team at Virginia Tech, led by Distinguished Alumni Professor Charles Reinholtz is another group that has made progress in developing a unique autonomous car platform. Their hard work and extensive research paid off in 2006 when they received the one million dollar contract to enter the DARPA Urban Challenge and received two donated Ford Escape Hybrids from Ford Motors to transform into self-driving cars (Haak 2007). The modified Escape that competed in the Urban Challenge, dubbed Odin, is pictured below.

Figure 3.5 (Team Victor Tango 2007)
The team describes their approach to the challenge as divided into three main parts: perception, planning, and the base vehicle platform. The perception component consists of the vehicle’s ability to identify its current position and perceive its surroundings, namely identifying and classifying obstacles in its path. The vehicle sensors pick up data and then send perception messages to the planning software. These messages consist of the localization component (current position and velocity of the vehicle), the road detection component (road coverage map and lane position), and the object classification component (detects obstacles and classifies them as either static or dynamic obstacles). The sensors responsible for gathering this data include two IBEO Alasca XT Fusion laser rangefinders in the front, one IBEO Alasca A0 unit in the rear, two imaging source color monocular cameras, and four SICK LMS 291’s (two mounted on the front corners, and one mounted on each side) (Reinholz 2007). The image below illustrates the thorough visual coverage provided by this sensor configuration.

Figure 3.6 (Reinholtz 2007)
The planning component of the vehicle’s functionality consists of a Hybrid Deliberative-Reactive model, meaning it has two independent components: one for upper level decisions and one for lower level reactions. This allows the car to react quickly in case of emergency without affecting the overall route plan. Finally, in terms of the base platform component, Team Victor Tango had the advantage of working with a Ford Escape Hybrid which already uses a drive-by-wire system. Thus they were able to control the stock steering, shifting and throttle systems electronically by simulating command signals. The diagram below illustrates beautifully the system architecture of Odin as a whole and how each of the components interacts with each other (Reinholtz 2007).

Figure 3.7 (Reinholtz 2007)
Another University sponsored group with an autonomous vehicle project underway is the Princeton Autonomous Vehicle Engineering group, or PAVE, at Princeton University. This primarily student-led team, consisting of 33 undergraduate students and eight faculty advisors, has been working on developing an autonomous car since 2004. Their first model, a silver truck donated by General Motors, dubbed ‘Prospect Eleven,’ made it to the final round of the 2005 DARPA Grand Challenge where it encountered a memory problem and shut down after completing 9.6 miles of the race. After determining that there was one line of code that was causing this problem and fixing it, the PAVE team took another shot at the 132 mile course on their own which the Prospect Eleven successfully completed, driving itself almost the entire time (Landau 2007).

Figure 3.8 (Landau 2007)
The team subsequently entered the DARPA Urban Challenge with the autonomous vehicle pictured above, a modified Ford Escape Hybrid donated by Ford Motors. The vehicle is equipped with a stereo camera that detects objects in its path and determines how far they are. Meanwhile, the tracking system determines the vehicles’ current position and keeps tabs on its position relative to surrounding objects (Landau 2007).

3.2 The Inherent Benefits of Autonomous Vehicles

Though each of these teams working on major autonomous vehicle projects uses different strategies and approaches toward achieving their goal, they can all agree on one thing: autonomous vehicles have the potential to reap direct and immediate benefits in the realms of accessibility, safety, and efficiency simply by just replacing the conventional automobile. Autonomously driven cars remove the elements of human error that makes driving so dangerous: namely lack of vigilance while driving, inconsistency of overall driving capability, and inebriation or impairment of any kind. Furthermore, their superior reaction speed in comparison to a human’s would not only make roads safer, but would allow cars to drive in a more fuel efficient manner and closer together, making better use of roadway space and easing congestion. Finally, autonomous cars could help overcome issues of mobility and accessibility, providing those who are unable to drive for any reason with a way to get around.

As previously noted, between 20 and 50 million people are injured in car accidents every year, and in 2002, 1.18 million people died from roadway crashes worldwide (Folsom 2011). Furthermore, “Traffic is the most dangerous thing that most of us ever encounter. From 2001 to 2009, American roads claimed 369,629 lives. And the culprit was not poorly lighted thoroughfares or faulty gas pedals but us—one landmark study cited ‘human errors’ as the ‘definite or probable causes’ of 93 percent of crashes” (Vanderbilt 2012). Sebastian Thrun and his colleagues at Google are convinced that autonomous vehicle technology would make roads much safer since autonomous cars “would react faster than humans to avoid accidents, potentially saving thousands of
lives” (Guizzo 2011). This is one of the greatest benefits to be reaped by the implementation of autonomous cars. “Primarily, self-driving cars have the potential to dramatically reduce the loss of human lives in automobile accidents, and the billions of dollars in associated costs” (Anthony 2011). Autonomous cars would also contribute to increased roadway safety by keeping drunk drivers off the road. In 2006, alcohol was involved in 41% of all fatal crashes in the United States, and autonomous vehicles could eliminate these accidents by providing inebriated drivers with a safe mode of transportation (Folsom 2011).

Removing the human element of driving would not only make roads safer by eliminating human error, but would increase efficiency both in terms of energy consumption and use of roadway space with the increased accuracy and reaction time of intelligent vehicles. Most human drivers operate their vehicles in a very fuel inefficient manner. “Aggressive driving (speeding, rapid acceleration and braking) wastes gas. It can lower your gas mileage by 33 percent at highway speeds and by 5 percent around town” (U.S. Department of Energy 2012). That translates into a waste of $0.19 to $1.28 per gallon spent on gasoline. Autonomous vehicles not only eliminate these factors of inefficient driving, but they also can be designed to drive at a constant, more fuel efficient speed which could be beneficial as illustrated based on the plot below.

Figure 3.9 (U.S. Department of Energy 2012)
The efficient driving of autonomous cars extends not only to fuel economy, but to a more efficient use of road space which could mean significant reductions of congestion. The Google team is convinced that “smarter vehicles could help make transportation safer and more efficient” (Guizzo 2011). Human following behavior while driving is an inefficient cycle of unnecessary acceleration to catch up to the car in front followed by breaking to maintain a greater distance because they need the extra space to accommodate their slow reaction time. The result is that “Even at its most packed, only about 5 percent of a highway’s surface is covered by automobiles; if cars were more hyperalert and algorithmically optimized, you could presumably squeeze many more of them onto the pavement” (Vanderbilt 2012). Autonomous vehicles would allow for just that. In fact, the Google team estimates that with autonomous cars we could make better use of 80 to 90 percent of the space left empty on roads. Furthermore, autonomous cars could safely operate at higher speeds on the freeway which would also help in reducing congestion (Guizzo 2011).

**3.3 Reaching the Full Potential of Autonomous Cars**

While the technology of autonomous cars clearly provides many benefits on its own, its true potential lies in its ability to overcome the obstacles associated with developing a new system of transportation, particularly those encountered by Personal Rapid Transit and car sharing. The main hurdle that developing PRT systems face is the extensive time and money required to put infrastructure in place—even for small test systems. Autonomous vehicle technology gives us the potential to create a new kind of PRT system with autonomous cars running on roadways instead of pod cars restricted to their own guideway. This kind of Shared Autonomous Taxi system would also greatly simplify testing. The few test PRT systems in place around the world consist of very small networks and still require significant investment to implement. Autonomous vehicles require an investment as well, but it can be put toward the building and testing of one or a few cars, and still give a comprehensive idea of how a fleet of them would perform on a larger scale. Another obstacle that autonomous vehicle technology
overcomes is the inconvenience of car sharing. Because autonomous cars can relocate themselves, they have the potential to make car sharing just as convenient, if not more convenient, than owning a private automobile.

The main problem with the capital required to implement a PRT system is that many are hesitant to be the first to make such an investment in a system whose value is not yet guaranteed. The fact that autonomous cars do not require as substantial an investment, and essentially no infrastructure, makes the possibility of their implementation much more realistic and probable. Vehicle performance can be measured by investing in building and testing just one car. Furthermore, even after the initial risk of investing in a PRT system is taken, the capital required to create more widespread systems would still be an issue. Vukan R. Vuchic, a professor at the University of Pennsylvania and critic of PRT argues that “there won’t be enough people to use PRT in the suburbs to make it profitable and in the packed downtown areas, there will be a need for bigger vehicles that could seat 30, 40, or even 80 people whereas PRT would be difficult to use” (Almasy 2011). Vuchic makes a valid point. In less populous areas there may not be enough traffic to offset the high costs of building a PRT system. With a Shared Autonomous Taxi system, the number of autonomous taxis in any location given the time of day can be easily controlled and varied based on travel demand. And because autonomous taxis can simply drive on existing roadways, there is no fixed cost for guideway infrastructure associated with implementing a Shared Autonomous Taxi system in a given location as there is for PRT.

In his critique of Personal Rapid Transit, Vuchic also argues that it is unrealistic to expect one mode of transportation to solve all of our problems. He argues that “modern transportation is designed as intermodal…It combines the use of private car and bus and light-rail and rapid transit and does not forget about pedestrians” and he goes on to say that “people like to think that there will be some vehicle that will come and that will solve everything…It’s a naïve concept” (Almasy 2011). His point about transportation being intermodal is certainly true, and that is part of the problem with PRT; it requires the same infrastructure and has the same capacity regardless of demand at a given time of day. However, his last statement may not hold true— a Shared Autonomous Taxi system arguably could solve the majority of our transportation issues.
because it has the potential to essentially combine multiple modes into one thereby maintaining the foundation of intermodal transportation that Vuchic argues is the essence of modern transportation. Furthermore, each element of our intermodal transportation system has its flaws:

Buses have the labor cost issue. Taxis have it even more, but are very convenient when available. Car sharing is great for certain types of trips, but you have to return the car to its starting point. With autonomous vehicles, there will be no need to differentiate between vehicles that carry many people on fixed routes (buses), vehicles that carry few people on demand (taxis), and vehicles you can drive but are only in certain places (car sharing) (Alpert 2010).

With the implementation of Shared Autonomous Taxis, “buses, taxis, and car sharing will essentially merge into one mode” (Alpert 2010), but still accommodate for the variety in types of demand that an intermodal transportation system addresses.

As previously discussed, an important piece in building a system that truly replaces the privately owned automobile is the concept of car sharing. In the aforementioned proposal of Smart-Para Transit by Mark Gorton, he emphasizes the importance of car sharing as the last piece of the puzzle in making the system a viable transportation alternative. He argues that “if Smart Para-Transit were paired with a car sharing program, nearly all driving scenarios would be covered, and this system would eliminate the need for car ownership for all but the most driving-intense” (Gorton 2008). The car sharing piece is important because it provides the same level of convenience as private automobile ownership, which Smart Para-Transit approaches but doesn’t quite reach. In fact, car sharing is arguably even more convenient than private car ownership because it removes the hassle of parking, which in turn is beneficial in reducing congestion. “Chronic parking shortages leads to cruising for parking which results in extra congestion, pollution, noise, and increased danger for children and senior citizens…Car sharing allows each car to be kept in service a much higher percentage of the time, and as a result, fewer cars are necessary to serve the same number of trips” (Gorton 2008). The downside to car sharing programs, like Zipcar, is that they require you to pick up and drop off vehicles at a specified location, adding an inconvenience that
doesn’t exist with private car ownership. This is another obstacle that Shared Autonomous Taxis could help overcome. Autonomous taxis allow for the implementation of a door to door car sharing service, making it just as convenient, or more convenient than private car ownership since there is never a need to search for parking. And most importantly they allow for the flexibility to share rides when appropriate or to travel alone otherwise.

The developers of the autonomous car at Google share Mark Gorton’s vision for a multifaceted system of Smart Para-Transit and car sharing, however their technology allows for the two to be combined into one system, or one fleet of autonomous cars. “Vehicles would become a shared resource, a service that people would use when needed. You'd just tap on your smartphone, and an autonomous car would show up where you are, ready to drive you anywhere. You'd just sit and relax or do work” (Guizzo 2011). Of course, in order to put a system like this in place autonomous vehicle technology must be perfected and any legal and social obstacles must be overcome, so for now it is still just a vision for the future. But in the meantime the team at Google is not only continuously working on perfecting their autonomous car, but is also experimenting with how this kind of system would work. “The project is still far from becoming commercially viable, but Google has set up a demonstration system on its campus, using driverless golf carts, which points to how the technology could change transportation even in the near future” (Guizzo 2011). Though the actual autonomy of golf carts is much simpler to implement than that of road vehicles, this demonstration is groundbreaking in that it is the first live simulation of how a Shared Autonomous Taxi system would function and benefit those to whom it is available. “The final leap here is to envision a self-driving car that can be commanded like an elevator. When a car can drive itself to our door whenever we want it, why own something that spends more than 90 percent of the time simply parked?” (Vanderbilt 2012). Herein lies the true potential of the developing autonomous vehicle technology. It allows for the most efficient use of automobiles possible—a system of Shared Autonomous Taxis that promote ridesharing when appropriate and function as a door to door car sharing service otherwise. Instead of sitting idly parked, unused cars can drive themselves to pick up new passengers, eliminating the need for widespread ownership of private automobiles.
Chapter Four
Transitioning to Autonomy
4.1 Potential Obstacles to the Implementation of Autonomous Cars

As autonomous vehicle technology continues to develop and the possibility of driverless cars operating on existing roadways becomes closer to a reality, obstacles to their widespread implementation outside the realm of technical perfection and reliability are beginning to arise. “Questions of legal liability, privacy and insurance regulation have yet to be addressed… such challenges might pose far more problems than the technical ones” (Markoff 2012). One of the most developed autonomous vehicle projects underway is the self-driving Toyota Prius at Google. And yet Google engineers themselves recognize “that there are many challenges ahead, including improving the reliability of the cars and addressing daunting legal and liability issues” (Guizzo 2011). Truly integrating autonomous vehicles into roadway traffic requires not only extremely reliable technology, but a significant transition in our society socially, psychologically, and legally.

The social and psychological barrier to autonomous cars consists essentially of two main issues: the apparent societal attachment to the conventional automobile and to driving, and concerns of safety when it comes to trusting computer operated vehicles on open roads. As autonomous car technology becomes more reliable, the need for a vigilant human driver, or any driver for that matter, in the vehicle is reduced. However, unmanned completely autonomous cars are unlikely to be allowed to drive among normal traffic until it is certain that there is no significant safety hazard and society has become comfortable with the idea—it is difficult to say when that point will be reached. As this process of socially and psychologically becoming comfortable with the idea of autonomous cars as a society continues, a simultaneous legal transition must occur. As autonomous cars begin to appear on roads, legislation must be drafted to address restrictions and regulations associated with their operation. And as society transitions away from the psychological need for a human driver to supervise, policymakers will have to reevaluate who is responsible for the vehicle: the driver or the manufacturer. There is a long road ahead for the widespread adoption and implementation of the
autonomous vehicle, but with a gradual reduction of the need for driver vigilance, the transition from human operated cars to autonomous cars should happen smoothly.

4.2 The Social Transition

The adoption of completely autonomous vehicles will require a change in some of the social and psychological norms that exist in our society when it comes to driving. Automated cars operating on existing roadways without any sort of guideway is a new concept that may take some time for people to get used to. Even the thought of riding in automated systems restricted to their own guideway was frightening to people at first as evidenced by the transition from manually operated to automated elevators and the gradual adoption of guideway-restricted automated systems like SkyBus. In the end these transitions were successful and people clearly have become comfortable with the thought of riding in automated systems based on the success of California’s BART and the systems in place at many airports. But integrating automated vehicles into existing roadway traffic is broaching unchartered territory and may require a similar gradual transition. The thought of driverless cars is foreign and therefore could cause some discomfort for people. Furthermore, there seems to be a strong societal attachment to driving and people might not want to give up the enjoyment that it provides. There also may be some societal hesitation toward the autonomous car that stems from concerns of how safe they really are. But the reality is that they are much safer than human operated vehicles; once people understand this and realize that letting go of the wheel means that they are free to sleep, get work done, talk on the phone, etc. rather than drive, it is likely that they will embrace this new technology.

4.2.1 Automobile Attachment and the Enjoyment of Driving

One possible social barrier to the widespread adoption of autonomous car technologies is society’s attachment to the automobile and to driving. But the real question is whether it is driving itself that people are attached to or simply the freedom
that the automobile represents and provides. If the latter is true, then autonomous vehicles should not be considered a threat because they preserve that freedom and simply remove the need to drive in order to achieve it. In fact, Google’s Chris Urmson, who scoffs at the idea that autonomous cars would take away from our freedom, says that autonomous vehicle technology “provides more freedom… If you’re disabled, if you’ve lost the privilege of driving, you can’t get around in American society. You’re stuck” (Vanderbilt 2012). In his mind, autonomous cars not only preserve the freedom to easily get around that society is so attached to, but they extend that freedom to those from whom it is withheld in the current system.

Chris Urmson further argues that attachment to the automobile stems from love of the freedom that it provides and represents, not the actual act of driving itself. In fact, “driving is often kind of a drag” (Vanderbilt 2012). As Urmson points out, “most of driving is not a car commercial” and most of the time people drive “with the purpose of getting from point A to point B, not with the purpose of winding through the mountains and enjoying *The Sound of Music*” (Vanderbilt 2012). More often than not, the sole purpose of driving is out of necessity with the goal to get from an origin to a destination rather than purely for the enjoyment of driving. And while driving can be an enjoyable and relaxing experience, there are certainly times when it can be more stressful than anything. Tom Vanderbilt illustrates this point in his article “Let the Robot Drive: The Autonomous Car of the Future is Here” for *Wired* Magazine as he describes his experience riding as a passenger in Google’s automated Toyota Prius. As they are driving along, “a car comes speeding along the adjacent on-ramp. Do we accelerate or slow? It’s a moment that puzzles many human drivers. Our vehicle chooses to decelerate, but it can rethink that decision as more data comes in—if, for instance, the merging car brakes suddenly” (Vanderbilt 2012). He makes a valid point; something as simple as deciding whether to accelerate or decelerate as a car tries to merge into your lane from an on-ramp can be a puzzling and even stressful experience for a driver. In an autonomous car like Google’s, the driver can sit back and relax while the vehicle instantaneously decides and executes the best course of action and remains vigilant and ready to adjust automatically should the situation change unexpectedly. It is just like being a passenger in a human operated vehicle, but with a much better driver. Furthermore, autonomous
vehicles do not completely remove the ability to drive oneself—if a person is overcome by the desire to take control of the wheel all they have to do is switch the car out of autonomous mode.

High tech features in newer models of many cars have already begun to address and relieve some of these human anxieties associated with driving. New features that add to both the convenience and safety of driving are continuously being developed and quickly becoming standard in mainstream commercial vehicles.

The truth is we have gradually been distancing our level of active engagement with the process of operating a car. We automated the shifting of gears. We went from manual steering to power steering and then finally to “drive-by-wire,” in which the mechanical connection between the steering wheel and the tires was replaced by a series of electrical impulses. We gave up paper maps for digital navigation systems. The hazards of parallel parking have been ironed out by ultrasonic sensors (Vanderbilt 2012).

These examples demonstrate the very gradual shift toward autonomy that has already begun to take place over time. They also illustrate the different stages of development and widespread adoption of these kinds of features. Consider the first example of automated gear shifting. It has become so mainstream that it is hardly even considered a ‘feature’ anymore. On the other hand, automated parallel parking is a relatively new technology that we consider more of a high tech automated feature that is only provided in the latest and most technologically advanced commercial vehicles.

One example of a high tech commercially sold car that approaches autonomy with all of its features is the new S-Class Mercedes whose Attention Assistance function was awarded the prize for best safety innovation by What Car?, the premier car buying guide in the UK. The Attention Assistance function helps monitor driver vigilance and keep fatigued drivers alert. The feature tracks over 70 elements of driver behavior that could indicate operator fatigue and alerts the driver by an audible tone and an icon on the dashboard that they should take a break if it detects signs of fatigue (Danielson 2010). The Attention Assistance function is just one feature of this very smart car. Tom
Vanderbilt, an S-Class Mercedes owner lists some of the key functions that the car performs for him:

If it rains, the wipers activate. If I enter a tunnel, the headlights adjust their illumination. When a car in the neighboring lane creeps into my blind spot, a red triangle illuminates in my side mirror; if I try to change lanes, the icon flashes and beeps. If I drift out of my lane, the steering wheel rumbles gently. The Distronic Plus system—Mercedes’ brand of what’s called adaptive cruise control—maintains a steady following distance, braking automatically when the car ahead slows. And if I’m about to crash and haven’t heeded earlier warnings, the car will take me out of the loop entirely, activating its robotic braking system and even rolling up the windows (Vanderbilt 2012).

The new S-Class Mercedes is a perfect example of the new breed of commercially sold automobiles whose smart features perform menial tasks like turning on the wipers for our convenience but also protect us from our own poor driving with features like blind spot sensors, adaptive cruise-control, and Attention Assistance.

Advanced car systems with features like those offered by the commercially sold S-Class Mercedes present a ray of hope for the adoption of full autonomous vehicle technology because if you think about it, “taken altogether, these automatic systems already approach full-blown autonomy” (Vanderbilt 2012). In fact, Mercedes is already developing a new feature for commercial vehicles called ‘traffic jam assist’ which controls speed with adaptive cruise control and steers as well, essentially giving drivers the option to sit back and enjoy the ride while the vehicle operates completely autonomously. If people can become comfortable with all of these automated features, especially the latest one being developed by Mercedes, then getting used to the idea of fully autonomous cars might not be such a great leap after all. Historically,

Each of these developments generated a brief period of resistance, which faded quickly as the new system began to seem natural. We do not feel as if we have lost something essential. On the contrary, in the same way that it would now feel strange to be in an elevator run by a human operator, it’s the absence of technology that begins to feel uncomfortable. Incrementally, more of the things that we think are innate
to the driving experience—steering, braking, accelerating—will be out of our hands (Vanderbilt 2012).

It may take time, but eventually people will not only become comfortable with the idea of fully autonomous vehicles on the road as they did with all other new automobile technology, but they will become uncomfortable with the thought of actually operating their own vehicle.

Although it is clear that autonomous car technology is certainly something that society could get used to, the possibility that part of automobile attachment is driving enjoyment and that people might actually miss the act of driving must still be considered. It is important to note, however, that automobile attachment, and relative driving enjoyment, may be a generationally dependent phenomenon that is on its way out. While in the recent past driving enjoyment may have been an important part of the attachment, contemporary automobile dependence is of a residual nature from that time period and is now viewed more as a means to an end. This hypothesis is validated by the fact that in the United States the number of young adults, under the age of twenty, who possess a driver’s license has decreased from about 12 million in 1978 to under 10 million in 2009 (Vanderbilt 2012). This certainly points to a generational shift in priorities when it comes to the automobile. Furthermore, “a recent Gartner report noted that nearly half of teenagers prefer an Internet connection to a car. (Only 15 percent of self-identified baby boomers said the same.)” (Vanderbilt 2012). Based on these statistics, it seems the age of the automobile is being left behind as the age of the Internet begins.

The new obsession with the Internet has even begun to exert its dominance in the realm of automobiles. Mercedes is the first automaker to offer “full Facebook integration” in their vehicles. This of course raises the question, “if your mind is also on Facebook, how much is left for traffic?” (Vanderbilt 2012). The same question regarding cell phone usage and texting has inspired many states to instate bans on talking on the phone or texting while driving. But “maybe the problem is not that texting and Facebook are distracting us from driving. Maybe the problem is that driving distracts us from our digital lives” (Vanderbilt 2012). This is certainly a new way to look at the clash between
technology and vigilant driving—one that would seem silly if not for the potential of fully autonomous cars. In the same vein,

futurists say that robotic cars could add to, not subtract from, driving enjoyment. In their view, it makes sense for commuters to blend into traffic, set a futuristic "cruise control," take their hands off the wheel and read, chat or do other tasks while the car safely speeds along at 90 mph a set distance from other vehicles, arrow-straight down the lane (Healy 2011).

Autonomous vehicle technology would allow passengers to perform alternative tasks like reading, texting and going on the Internet in the time that they normally spend driving. And in this new technology and Internet obsessed era, that just might be enough to overcome any other psychological and social hesitations regarding autonomous cars.

4.2.2 Addressing Safety Concerns

Part of the social and psychological discomfort associated with the idea of autonomous cars stems from concerns of safety. “The problem is no one really knows how safe millions of computer-controlled cars would actually be. Software can be buggy, after all—and you really don’t want your car to suffer the automotive equivalent of a blue screen of death while doing 100 mph in the fast lane” (Anthony 2011). The concern of how safe it is to have autonomous cars operating on open roads rather than on a segregated and controlled guideway may be another social barrier to the adoption of this new technology. With this in mind, autonomous car developers continue to test and rework their cars and equip them with backup systems in case of failure, improving the reliability of their systems to ensure that they are completely confident in their technology before autonomous vehicles enter the commercial automobile industry. Furthermore, when questioning the safety of autonomous vehicles operating on existing roadways, it is important to consider not just their absolute safety, but their increased safety relative to that of cars operated by human drivers.
Given that it is a new technology and that it takes the outcome out of the driver’s control, the autonomous car may seem scary and dangerous, but how dangerous is it really in relation to human drivers? The danger of human operated vehicles on the road is vastly underestimated. As has been established, most traffic accidents are a result of some sort of human error. The beauty of the autonomous car is that it removes all of the variables that make human operated vehicles so dangerous including distractions, laziness, lack of vigilance, slow reactions, drowsiness, hastiness, and just plain poor driving. “On principle, it would seem downright churlish to penalize Google’s upstanding Prius — which kept letter-perfect lane position, following distance and speed-limit compliance — while all around us human drivers committed a panoply of illegal acts: talking on their phones, speeding, changing lanes without signaling, tailgating, you name it” (Vanderbilt 2012). And even putting all of those human driving faux pas aside, the truth is autonomous cars can still easily outperform even the most competent, alert and law abiding human driver. “It can think faster than any mortal driver. It can attend to more information, react more quickly to emergencies, and keep track of more complicated routes. It never panics. It never gets angry. It never even blinks. In short, it is better than human in just about every way” (Vanderbilt 2012). Autonomous cars not only outperform humans in every human aspect of driving, but they perform advanced functions like predicting the future that humans do not even attempt. Google’s automated Toyota Prius analyzes and predicts the state of the world surrounding it an astounding twenty times per second—much faster than any human can or would care to. The car observes, considers and reacts to much more than any human driver is aware of. For example driving along on the freeway, it notices a car in the adjacent lane about thirty feet ahead and slows ever so slightly to avoid being in that driver’s blind spot (Vanderbilt 2012).

But most importantly, the autonomous car is not just a robot on wheels, programmed to function in the ‘perfect’ way. It is designed to adapt to human behavior and drive like a human (but better), and sometimes that means driving imperfectly. As a large bus pulls alongside Google’s automated car on the freeway, the Prius drifts slightly to the left creating distance between itself and the bus on its right. Anthony Levandowski, the business lead on Google's autonomous car project, points out that
“even if you can drive in the center of the lane, down to the centimeter, that doesn’t mean it’s the safest route” (Vanderbilt 2012). The informational capacity, quick reaction time and prediction ability of autonomous cars allows them to drive just like a human, but better. This, along with the fact that they remove the element of variability in human driving ability and alertness makes autonomous vehicles very safe in absolute terms and even more so when compared to the safety of human operated vehicles.

4.2.3 SkyBus: A Comparable Social Transition

In considering the pending social and psychological transition toward the autonomous car, it may be helpful to look to a similar past transition: the SkyBus system developed by AEG Transportation Services Incorporated. The system was developed after the initial boom of the automobile in an effort to reduce congestion and although it achieved technical success very quickly, it took years to gain the societal acceptance necessary for widespread implementation.

The number of cars on the roads doubled between the years 1940 and 1960 introducing a severe problem that is still prevalent today: congestion. When this problem first began in the 1960’s, planners everywhere began looking for a way to reduce traffic congestion. Engineers at Westinghouse Electric Company, now AEG Transportation Services Inc., developed a new transit concept called SkyBus: a completely autonomous bus that runs on an elevated guideway so as to keep it separate from normal traffic and help reduce congestion on roads. The SkyBus engineers teamed with the Port Authority of Allegheny County in Pennsylvania who was looking for exactly this kind of revolutionary system. After funding was approved, construction of a 2 mile long elevated guide way test track began in South Park, Pennsylvania about 10 miles south of Pittsburgh. After long hours of testing, they achieved their goal and SkyBus first completed the circuit in August of 1965. The system was formally unveiled to the public in September 1965 at the Allegheny County fair. People were impressed by its advanced electrical propulsion system which made it fast, clean and non-polluting and by how
quietly it sped along the guide way. Most of all, however, people were blown away by
the fact that it was fully automated and needed no driver (Atlantic Media Group 2010).

Although the system was running completely automatically, the busses were
manned by an operator in order to make passengers feel more comfortable. The company
felt this was necessary since this kind of automated system was a brand new concept.
They worried that people would react the same way that they did when elevators first
switched from manual to automated; automated elevators were manned by an operator
who just sat there and pushed the buttons for passengers for six months to a year before
the new technology was accepted by the general public. So, in its initial unveiling,
SkyBus was manned by an operator to help ease people into the idea of the automated
system without scaring them off. Throughout the following year, SkyBus continued to
prove its functionality through all of the seasons and passed all government testing and
field observations with flying colors. So, feeling very confident as the subsequent county
fair arrived, the SkyBus team allowed the system to run the way it was intended to,
completely unmanned, and the passengers who rode it at the fair loved it (Atlantic Media
Group 2010).

Based on their success at the Allegheny County fair, the SkyBus team published
its test report in February of 1967 saying that the concept had worked out extremely well
and should be further developed into a full blown commercial system. The future of
SkyBus looked promising as the Port Authority of Allegheny County began building a
10.5 mile track from South Hills to downtown Pittsburgh. Unfortunately, some nearby
communities voiced concerns about a transit system that operates without a driver and as
a result the project was delayed, and eventually killed. Bill Segar, Manager of
Engineering/Technical Services at AEG Transportation Services says simply that “the
biggest problem of all was that it was a new technology.” And just like that the whole
project was terminated and the test track in South Park was eventually torn down—it
looked like the end for SkyBus (Atlantic Media Group 2010).

Nevertheless, the creators of SkyBus remained optimistic. They believed in their
technology and felt that the only problem was that they did not have an application yet,
and so the marketing team got to work brainstorming ideas of how to apply this great
technology to solve existing transit problems. Their first big application opportunity
came in 1970 at the Tampa International Airport, and that was only the first of many. The next big victory for SkyBus came when their technology was implemented in San Francisco’s Bay Area Rapid Transit, or BART, revolutionizing the entire transportation industry with the first fully automated mass transit system in the world. However, even Bart was worried that passengers would be wary at the idea of driverless transit so they added on board personnel to ensure passengers’ comfort. As SkyBus applications began to grow (today there are over 200 SkyBus vehicles in service or under construction), people gradually got used to the idea of riding a transit system without a driver. Driverless SkyBus technology currently transports over a billion people each year in airports, cities, and real estate developments around the world. John Tucker, the President of AEG Transportation System attributes this incredible bounce back from their initial failure to the fact that “once people become accustomed to the reality that a system can be used and can be used safely, it’s amazing how quickly that fear passes. With the continued use of our systems, and by now they’re quite popular both here in the United States and around the world, that fear has diminished to zero” (Atlantic Media Group 2010).

The present concerns associated with the operation of autonomous cars on public roadways is comparable to the fear initially felt by passengers of autonomous transit systems like SkyBus. SkyBus’s history demonstrates that it is a difficult hurdle to overcome, but once that first implementation is in place people will start to get used to the new technology and the fear will diminish. It also suggests that a possible stepping stone for this transition is to have an operator on board to make users feel more at ease, similar to the concept of having a vigilant human driver supervising and ready to take over in an autonomous car until society comfortable with the idea of them driving around with a sleeping passenger or even completely empty.

4.3 The Legal Transition

One of the most daunting obstacles in the way of incorporating autonomous vehicles on existing roadways is the host of legal issues that must be dealt with first.
Though autonomous vehicle technology is well on its way to becoming reliable enough to navigate traffic, “the legal and liability landscape is essentially uncharted” (Vanderbilt 2012). Google’s Anthony Levandowski points out that the autonomous vehicle technology has far outpaced the corresponding legislation (Vanderbilt 2012). As Google has been testing its autonomous car on California roadways based on the assumption that, since the law does not address autonomous vehicles, it is safe to do so as long as they are manned by a human driver who is ready to supervise or take over as needed. The operation of these vehicles on California roads and questions regarding what kind of legislation should be implemented make for an interesting case to examine in the exploration of legal issues associated with autonomous cars. Somewhat surprisingly, California is not the first state looking to address these issues in the immediate future. “Nevada is the first state to pass a law making driverless cars legal, and bills have been introduced in California, Florida, Hawaii and Oklahoma. Arizona introduced a bill, but it failed” (Priddle 2012). However, these bills are just a starting point as they simply direct the state’s Department of Motor Vehicles to impose regulations and restrictions regarding the testing and operation of autonomous vehicles on public roads.

Dealing with legislation regarding the operation of autonomous vehicles is highly complicated and will require lawmakers to consider a plethora of questions from what exactly defines a vehicle as autonomous to who is responsible for the vehicle should an accident occur. The transition from human operated to autonomous vehicles is likely to be a drawn out process. “For as long as anyone, even Google, is willing to predict, cars will by necessity be semiautonomous; human drivers will still have to play some role. But figuring out what that role will be is complicated. Are we pilots or copilots? How far out of the loop can we be taken?” (Vanderbilt 2012). In theory, autonomous vehicles have the potential to take human drivers completely out of the loop. But getting there will most likely require a gradual process of reducing required driver vigilance while increasing autonomous vehicle reliability and experience, and will require comprehensive legislation to guide this transition.
4.3.2 Nevada State Law

On February 15, 2012 Nevada became the first U.S. state to officially allow autonomous vehicles to operate on public state roads with Assembly Bill 511, “authorizing in this State the operation of, and a driver’s license endorsement for operators of, autonomous vehicles” (Nevada State Assembly 2012). The Bill mandates that the Nevada Department of Motor Vehicles must “adopt regulations authorizing the operation of autonomous vehicles on highways within the State of Nevada” (Nevada State Assembly 2012) that specify the standards that a vehicle must meet before operating on roads, address the insurance required to test and operate these vehicles, and establish any other regulations that may be necessary. Furthermore it requires that the Nevada DMV establish a license endorsement that will “in its restrictions or lack thereof, recognize the fact that a person is not required to actively drive an autonomous vehicle” (Nevada State Assembly 2012).

As mandated by Assembly Bill 511, the Nevada Department of Motor Vehicles laid out a set of regulations regarding autonomous vehicles in Adopted Regulation R084-11 effective March 1, 2012. The regulations begin by defining an autonomous vehicle as “enabled with artificial intelligence and technology that allows the vehicle to carry out all the mechanical operations of driving without the active control or continuous monitoring of a natural person” (Nevada Department of Motor Vehicles 2012), specifically excluding vehicles enhanced with driver assistance systems like adaptive cruise control, parking assistance, crash avoidance, etc. Only then do they begin to address the associated regulations for testing and operating such vehicles and the licensing of drivers who wish to operate them.

The legislation states that in order to test an autonomous vehicle one must submit an application to the Department of Motor Vehicles. Approval for this kind of license is contingent upon certain requirements for the vehicle: it can safely operate on roadways, it has an easily accessible switch to engage or disengage from autonomous driving mode, it has a safety system that alerts the driver to take over if technology failure is detected, and it “has a separate mechanism in addition to, and separate from, any other mechanism required by law, to capture and store the autonomous technology sensor data for at least
30 seconds before a collision occurs between the autonomous vehicle and another vehicle, object or natural person while the vehicle is operating in autonomous mode” (Nevada DMV 2012). Once a testing license is approved, the vehicle may be tested in authorized locations specified by the license. The vehicle must be physically manned by two regularly licensed drivers who are trained in operating autonomous vehicles at all times during testing. Furthermore, one of these people must assume the role of the ‘driver’ and be in position to take over control at any given moment. Another stipulation placed upon the testing license is that if an accident occurs it must be reported to the DMV within ten days. Additionally, applicants must apply for temporary license plates which indicate that the car is an autonomous vehicle that is undergoing testing (Nevada DMV 2012).

The Nevada DMV also sets out regulations regarding the commercial use of autonomous vehicles. Before being sold commercially, an autonomous car must obtain a certificate of compliance from the manufacturer or an autonomous technology certification facility which verifies it meets certain requirements, similar to those required to allow testing but with some notable additions. Again the vehicle must safely operate on roads and have an easily accessible way to engage and disengage autonomy, but it must also be equipped with a visual cue in the car that indicates when the car is operating autonomously and when system failure occurs must require the driver to take over, or, if there is no driver present in the vehicle, it must be able to safely remove itself from traffic and come to a safe stop. If a person wishes to operate such a vehicle they must obtain a G endorsement on their driver’s license. Upon registering the vehicle, they will obtain license plates, different from those issued to test vehicles, which indicate that the vehicle is autonomous. At this point, the vehicle will be allowed to operate completely autonomously on all Nevada roadways—with or without the licensed operator. In an attempt to address the obvious liability issues that this presents, the law states that “a person shall be deemed the operator of an autonomous vehicle which is operated in autonomous mode when the person causes the autonomous vehicle to engage, regardless of whether the person is physically present in the vehicle while it is engaged” (Nevada DMV 2012). Thus the responsibility for the vehicle’s actions remains in the hands of the
licensed operator, regardless of whether they are in the vehicle or not (Nevada DMV 2012).

The regulations set forth by the Nevada Department of Motor vehicles are quite progressive in that they address not only the testing of autonomous vehicles which is currently very applicable, but the future commercial operation of autonomous vehicles as well. It also specifically addresses the human role in operation of autonomous vehicles. If a vehicle meets all of the requirements to become street legal, it can be operated by a G licensed driver whether or not they are in the vehicle. The standards are such that if a vehicle can pass them, it is assumed that it can operate safely on public roads without anyone in the vehicle. In concurrence with this important piece of legislation, the DMV also addresses the associated question of liability in its statement that the individual who engages the autonomous car is fully responsible for that vehicle regardless of whether they are inside the vehicle.

4.3.1 California State Law

California is one of a handful of states that seem to have been inspired by Nevada’s legalization regarding the operation of autonomous vehicles on state roads. State Senator Alex Padilla “wants the Golden State to follow the same trail blazed by Nevada” (Squatriglia 2012) and believes that “California, with its thriving tech sector, is the perfect testbed for such technology” (Squatriglia 2012). So in late February following the announcement of Nevada’s new legislation, he rode to the California state capital, in Google’s autonomous Toyota Prius no less, to announce legislation that would formally allow and regulate the operation of autonomous vehicles on California roads. The proposed Senate Bill 1298, which similar to Nevada’s Assembly Bill 511, mandates that the California Department of Motor Vehicles “adopt safety standards and performance requirements to ensure the safe operation and testing of ‘autonomous vehicles’” (California State Senate 2012) on the state’s public roadways.

Similar to the Nevada Bill, SB 1298 defines an autonomous vehicle as “a motor vehicle that uses computers, sensors, and other technology and devices that enable the
vehicle to operate without the active control and continuous monitoring of a human operator” (California State Senate 2012), again specifically excluding vehicles equipped with advanced driver assistance functions. This legislation directly addresses the testing of autonomous vehicles in California by Google and others that has already been going on for some time, condoning the efforts and even citing them as inspiration for the proposed legislation.

The State of California, which presently does not prohibit or specifically regulate the operation of autonomous vehicles, desires to encourage the current and future development, testing, and operation of autonomous vehicles on the public roads of the state. The state seeks to avoid interrupting these activities while at the same time creating appropriate rules intended to ensure that the testing and operation of autonomous vehicles in the state are conducted in a safe manner (California State Senate 2012).

Such regulations and safety standards are yet to be put in place by the California DMV, and unlike Nevada’s Assembly Bill 511, California’s SB 1298 does not specify a deadline by which they must be implemented. However, the bill also clarifies that “this does not prohibit the operation and testing of autonomous vehicles on the public roads in this state on or before the adoption of regulations by the department” (California State Senate 2012). Thus the testing of autonomous vehicles will be allowed to continue as it has been until the California DMV puts specific regulations into effect. When they do, it will be interesting to see how the requirements compare to those implemented in the state of Nevada.

4.3.3 Vehicle Liability

As states like Nevada and California begin to navigate the appropriate legislation associated with autonomous vehicles, they must address the complex and extremely important issue of liability. The development of autonomous technologies—and not just full autonomy—is forcing policymakers to start examining these issues. “As increasingly
autonomous technologies enter our cars, the legal questions, liability in particular, have
grown more relevant” (Vandenburg 2012). The RAND Corporation points out that “as
these technologies increasingly perform complex driving functions, they also shift
responsibility for driving from the driver to the vehicle itself…. [W]ho will be
responsible when the inevitable crash occurs, and to what extent? How should standards
and regulations handle these systems?” (Vandenburg 2012). A large part of the transition
from human operated vehicles to autonomous vehicles will be answering these questions
through legislation that regulates the operation of autonomous cars on public roadways.
All legislation in this realm will have to be very adaptive and constantly address the ever
improving technology and reliability of the vehicles as well as the level of social
acceptance associated with their operation. Specifically, it must address whether there
must be a human operator in the vehicle standing by and if so how vigilant that driver
must be.

Though legislation regarding fully autonomous vehicles magnifies the importance
of clarifying questions of liability to the extreme, these issues have been around for a
while. Stanford Law School’s Center for Internet and Society is currently working on
examining the current legal framework for ‘quasi-autonomous vehicles’. Ryan Calo, the
director for privacy and robotics, points out that the liability landscape in terms of safety
features on cars is already very active. He says “people sue over all kinds of stuff.
People sue because some feature that was supposed to protect them didn’t. People sue
because their car didn’t have a blind-spot warning when other cars at the same price point
did” (Vandenburg 2012). Issues of liability are already very present in the automobile
industry—full vehicle autonomy is simply a catalyst that forces policymakers to finally
address them comprehensively. Of course, full vehicle autonomy does bring about a new
level to the whole slew of liability issues. “Imagine the complexity we’ll have when cars
drive themselves. Who will be responsible for their operation—the car companies or the
drivers? What happens, for example, when a highway patrol officer pulls over a self-
driving car? Who gets the ticket?” (Vandenburg 2012). The realistic answer is that only
time, and the corresponding progress toward developing and implementing autonomous
vehicle technology, will tell. For the foreseeable future, autonomous cars will be manned
by human drivers who will be required to remain as vigilant as if they were driving their
own car and the liability will remain in their hands. However, as autonomous cars prove their reliability and people become more comfortable with the idea of being chauffeured by their car, the responsibilities of the human operator may fade to the point where eventually autonomous cars can be completely unmanned, at which point the liability may have to rest upon the manufacturer. It is the grey area between these two extremes where liability gets hazy and accordingly, legislation will have to carefully specify the amount of liability placed upon the driver versus the manufacturer.

Assuming this eventual shift in liability is inevitable, “potential liabilities will be huge for the designers and manufacturers of autonomous vehicles” (Markoff 2012). One way to address this possible deterrent toward producing autonomous cars is to offer some lenience in the way of manufacturer liability. “For example, liability exemptions have been mandated for vaccines, which are believed to offer great value for the general health of the population, despite some risks” (Markoff 2012). Autonomous vehicles may fall in that same category—as with the operation of any automobile there are some risks, but the safety benefits are paramount in comparison. This kind of policy may not even be necessary, however. The issue will probably resolve itself in the way that it did when air bags were first introduced. Automobile manufacturers were initially opposed to the implementation of air bags because they feared that it could shift responsibility for passengers’ safety from drivers to themselves. But once the technology was out there people expected it to be used, and sued automakers for not having air bags in their cars when at the car’s price point they should. Clearly the hurdle of hesitance by automakers was overcome considering that air bags are considered standard equipment in commercial vehicles today. Similarly, liability concerns may not “hold up the adoption of safety-oriented autonomous technologies” (Vanderbilt 2012). In fact, given that autonomous cars will reduce the number of automobile crashes and thereby lower insurance costs, there may actually be an extra push from drivers and automobile-insurance companies to get these vehicles on the road (Vanderbilt 2012). All in all, liability concerns on the part of the automakers manufacturing the cars, the companies insuring them, and lawmakers regulating their use on public roadways should not deter the adoption of autonomous vehicle technology. Nonetheless, liability is certainly an issue that must be addressed as
the technology advances and society transitions toward the widespread implementation of unmanned autonomous vehicles.
Chapter Five
A Shared Autonomous Taxi System
5.1 Implementing a Shared Autonomous Taxi System

The development of autonomous vehicles is a new and exciting technology full of possibilities. As previously discussed, simply replacing human operated automobiles with autonomous ones would reap significant benefits in terms of safety, efficiency and congestion. But the real potential of autonomous vehicle technology is that it makes possible the implementation of an entirely new transportation system that is even more convenient than the current use of the conventional automobile and simultaneously addresses all of the major issues associated with automobile dependency. The ideal implementation of autonomous vehicle technologies is a new system, a fleet of Shared Autonomous Taxis, that functions both as a rail-less PRT system to promote ridesharing and ease congestion during peak hours and a personal Taxi system that provides the convenience of door to door service by shared cars in off peak hours when demand for Taxis is reduced and congestion is not an issue.

During peak hours, the Shared Autonomous Taxi system would function much like a Personal Rapid Transit system, but running on existing roadways rather than on a separate guideway. Passengers could request a trip ahead of time from their computer or phone, and then walk to the nearest taxi stand where they would enter a waiting autonomous taxi which would be shared by other passengers taking a trip within a couple of minutes of theirs to a nearby destination or along a similar route. Or for a premium, the passenger could opt for door to door service where they would be picked up by their autonomous taxi and still potentially stop for passengers with a similar route along the way. In this sense, the Shared Autonomous Taxi system functions much like the Smart Para-Transit system proposed by Mark Gorton, but without drivers. Autonomous car technology not only allows for a blend between these two styles of transportation systems, PRT and Smart Para-Transit, but it overcomes the major obstacles associated with each: for PRT, the extensive infrastructure, and for Smart Para-Transit, the fact that “a large number of drivers would be required to pilot the fleet of vehicles and demand for drivers and vehicles would be uneven over the course of the day” (Gorton 2008). Which brings up another benefit of the flexibility provided by autonomous taxis: the functionality of the Shared Autonomous Taxi system can be completely tailored to
changing demands throughout the course of the day. Clearly, the way it operates during peak hours places an emphasis on ridesharing in order to ease congestion. But during off peak hours, the system could function as a driverless, door to door taxi system, completely eliminating the need to personally own an automobile.

The key to the Shared Autonomous Taxi system is autonomous vehicle technology and the ability for autonomous cars to drive on public roadways completely unmanned. And though the development of autonomous vehicle technology is well on its way to making this a possibility, based on the social and legal obstacles that have been discussed, it could take some time before this becomes a reality. In the meantime, it would be prudent to incorporate the development of a Shared Autonomous Taxi system into the gradual transition toward the acceptance of autonomous vehicles. This would ensure that when the world is ready to see these autonomous taxis drive on their own, the system will be in place to take full advantage of that in the best way possible. It seems that for the foreseeable future, having a human driver supervise the operation of autonomous cars will be a firm requirement. In order to move away from that restriction, people need to see and experience the reliability of automated cars first hand. So, logically the first step of the transition is to simply begin substituting autonomous cars for human operated cars without changing the system. This will allow people to get comfortable with the idea of letting their car drive itself and open up to the idea of allowing these cars to drive themselves without human supervision. And in the meantime, there will still be some significant benefits reaped in terms of safety, efficiency and congestion. While this societal psychological transition is taking place, the implementation of the taxi system should be happening in parallel. The promotion of ridesharing upon which the Shared Autonomous Taxi system is based will require a computer system that takes in all requested passenger trips and groups them based on origin, destination and departure time. It might also be useful to start implementing test systems, in New York City for example as proposed by Mark Gorton, operated by cars with drivers so that when people are finally ready to let go of the wheel and completely trust autonomous vehicles operating on their own, it will be easy to make the switch over to the Shared Autonomous Taxi system.
5.2 A Basic System to Satisfy Demand During Peak Hours

Where a Shared Autonomous Taxi system really revolutionizes the transportation industry is in its ability to significantly ease congestion during rush hour traffic. In order to understand this it is helpful to visualize how a very basic system would look and function in the real world, and so this thesis examines how a Shared Autonomous Taxi system might serve the travel demand of a real medium density suburban area, as represented by Mercer County, New Jersey.

5.2.1 Detailed Travel Demand

The typical weekday travel patterns of all people living and/or working in New Jersey were generated by a group of Princeton University students enrolled in the Operations Research and Financial Engineering department’s course on Transportation Systems Analysis in the fall of 2011. The U.S. Census and other sources were used to synthesize each person living and/or working in New Jersey. Distributional assumptions about the demand for travel by individuals and the chaining of trips allowed for the specification of precise origin, destination and departure time for each trip made by each in-state resident and each out-of-state resident working in New Jersey on a typical weekday. For the purpose of this thesis, only the trips originating in one county were analyzed to give an in depth example of how a basic Shared Autonomous Taxi system would serve travel demand. Mercer County was chosen because its population density is in the mid-range of New Jersey counties and because Princeton University is located in this county. According to this data set, on a typical week day 1,289,727 trips are made in Mercer County. Each of these trips is specified by a precise origin and destination location (latitude, longitude) as well as a precise departure time (in seconds after midnight). Also available is the purpose of each trip and the name, age and sex of the person making the trip.

In order to get an idea of how a Shared Autonomous Taxi system might serve Mercer County, a very basic model of implementation is assumed—dividing the county
into half mile by half mile areas and assuming that all trips originating from a given quarter square mile area would be served by a taxi stand located at the centroid. A Shared Autonomous Taxi system is designed based on the assumption that users will walk to the nearest taxi stand where they will enter an autonomous taxi, wait a short predetermined period of time in case another person arrives who can share the ride, and then proceed non-stop to the destination taxi stand nearest the passengers’ desired destination. A key to the design of this system is the precise location of taxi stands to serve as many trips as possible which can be determined by examining trip densities in an area. An optimal number and distribution of taxi stands is beyond the scope of this thesis; however, a nominal, less than optimal design is one where taxi stands are uniformly distributed then analyzed so that stands with very limited demand can be eliminated. It is reasonable to assume that people will accept a five minute walk to and from taxi stands which translates into a distance of about a quarter mile. Based on this assumption, the design analyzed in this thesis is created by pixilating Mercer County into a grid composed of pixels that are a half mile wide by a half mile high with taxi stand located in the center of each “pixel.” Given this pixilation, it was straightforward to determine the Mercer County pixel where each trip originates and terminates and thereby assign trips to a particular taxi stand.

To analyze this setup and the resulting trips served by each taxi stand, trips must first be assigned to an origin pixel. In order to assign trips based on the origin data which is given in latitude and longitude to a particular taxi stand, a conversion formula is created, using the following formula for approximating distance in miles given latitude and longitude as a starting point:

$$\text{distance in miles} = \sqrt{\left[ (69.1 \times (\text{lat}_2 - \text{lat}_1))^2 + (69.1 \times (\text{lon}_2 - \text{lon}_1) \times \cos(\text{lat}_1/57.3))^2 \right]}$$

(Meridian World Data)

This formula can be manipulated to determine the change in longitude that translates to a half mile at constant latitude, and the change in latitude equivalent to a half mile at constant longitude, which allows Mercer County to be broken up into half mile by half mile pixels to which trips can easily be assigned. The following image illustrates this
method (the grid overlay is not to scale—the actual half mile increments are much smaller).

![Figure 5.1 (Google Maps)](image)

The point at 38°N of latitude and 73°W of longitude is used as a starting reference point for the bottom left corner of the grid, such that the following formulas could be used to convert from latitude to the number of half mile intervals away from the reference latitude, and similarly from longitude to the number of half mile intervals from the reference longitude.

1. Latitude HMI = 138.2(latitude – 38)
2. Longitude HMI = 138.2(longitude – 73) * cos(latitude/57.3)
Truncating the resulting number of half miles from the starting reference point (38° or 73°) creates a simple index for each trip origin by latitude half mile index (HMI) and longitude HMI. For example, the trip originating at the latitude and longitude coordinates (40.26386, -74.48875) becomes a member of the group of trips indexed at (312, 157) which contains all trips located in the area between 312 and 313 half miles away from latitude 38°N and between 157 and 158 half miles away from longitude 73°W and served by the taxi stand at the centroid of that pixel. The following scatter plot shows all Mercer County trips plotted by the number of half miles from the reference point (the origin of the plot). Each increment of one on each axis represents a half mile, such that all of the points that fall in the same one by one square on the plot are served by the same taxi stand.

**Mercer County Trips**

![Figure 5.2](image)

Once all of the trips have been indexed and assigned to a taxi stand, the travel demand at each stand can be examined. In assigning all of the trips to a half mile by half
mile pixel, it appears that 10,130 of them contain the origin of at least one trip. Of these, 4,637 contain the origin of more than ten trips, 1,198 of more than one hundred, 301 of more than one thousand, and 9 of more than ten thousand. If there were a taxi stand located in each of these 10,130 total areas, the average number of trips served by each taxi stand would be 127.2988. The following histograms illustrate the trips served by taxi stands that see ten or more trips in a day, focusing on areas of higher trip densities where a Shared Autonomous Taxi system would have the most impact in promoting ridesharing. They are organized to show the number of taxi stands with trips served from 10 to 100 by tens, 100 to 1,000 by hundreds and 1,000 to 23,000 by thousands.

![Taxi Stands Serving 10 to 100 Trips/Day](image)

**Figure 5.3**

![Taxi Stands Serving 100 to 1,000 Trips/Day](image)

**Figure 5.4**

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At first glance it already seems that there is enough consolidation of trips to make the implementation of Shared Autonomous Taxis worthwhile, even with taxi stands that are distributed in this arbitrary, uniform manner. But in order to truly demonstrate the system’s ability to promote ridesharing it is important to consider the element of timing. The more people show up at a taxi stand during a short time interval, the higher the
probability of rides shared. Based on the amount of rush hour traffic, it is likely that these taxi stands will see high trip consolidation during the morning and evening commute hours. This hypothesis can be verified by examining the distribution of trips throughout the day at one taxi stand. Examining the taxi stand that sees the most trips in a day will provide the most data points to analyze. This stand serves 22,926 trips and is indexed by (324,174). Converting back to latitude and longitude, this represents the area spanned from 40.3444°N to 40.3517°N and 74.6519°W to 74.6615°W which is located in Princeton, New Jersey. In this model, the taxi stand that would serve the half mile by half mile pixel outlined on the following map would be located in the heart of Princeton University.

![Figure 5.7 (Google Maps)](image)

The following histogram illustrates the number of arrivals to this taxi stand during each minute throughout the entire day. The pattern demonstrated at this taxi stand is typical of general traffic patterns throughout the day: a higher narrow peak during
morning rush hour and a slightly flatter and more extended gradual peak during the evening commute home from work. The histogram shows that this particular taxi stand would see 78 arrivals during the busiest minute of morning rush hour, and a fairly consistent rate of twenty to seventy arrivals per minute during both periods of peak hour travel.

The analysis of the Princeton taxi stand demonstrates the benefit that a Shared Autonomous Taxi system could have, especially in similar areas where travel demand is highly concentrated. The high volume of people departing from the same location in short periods of time presents boundless opportunity for ridesharing that would otherwise
not occur. If twenty to seventy people are arriving at the taxi stand each minute during peak hours as they would in Princeton, the probability that two or more are travelling to the same destination, a similar destination or even along a similar route is high. And allowing a two to five minute waiting period from when a traveler steps into their taxi to when that car departs for more potential ride sharers to arrive further increases that probability. This presents one important element of further research to be conducted in the process of implementing a Shared Autonomous Taxi system. Different wait times must be analyzed to find an optimal balance between high autonomous taxi occupancy and the convenience of a short wait. The result would probably vary based on the location and travel demand of each individual taxi stand. Another important area of further research is determining the optimal location for taxi stands. In this model, the centroid of arbitrarily divided half mile by half mile pixels is used to locate taxi stands in order to get an idea of what the consolidation of travel demand in Mercer County would look like. It is likely that a more efficient allocation of taxi stands could serve a higher number of trips and possibly catch some of the outliers that fell into areas of low travel demand in this model.

5.3 Reaping the Benefits of Shared Autonomous Taxis

As has been discussed, autonomous vehicles provide a wealth of benefits in terms of safety, efficiency, and congestion. Using the technology to implement a Shared Autonomous Taxi system adds even more benefits in terms of convenience and most importantly in significantly reducing congestion during peak hour travel. Because the Shared Autonomous Taxi system offers door to door service, its level of convenience is comparable with that of the conventional automobile. However, because it also removes the need to own a car at all and concurrently all of the maintenance and other hassles associated with car ownership, it is actually even more convenient than the current system based on private car ownership. Furthermore, Shared Autonomous Taxis remove the need for parking which adds to convenience, allows for better use of the land needed for parking lots and structures, and removes congestion caused by drivers trolling for
parking. But the ways by which a Shared Autonomous Taxi system would ease congestion most notably are with the promotion of ride sharing discussed in the previous section and with the increased number of more efficiently driven vehicles associated with the implementation of the system.

The driving behavior that humans demonstrate when following a vehicle is very inefficient. PELOPS, a traffic simulation program created by Kraftfahrwesen Institute and BMW in Germany uses the Weidmann model to characterize driver behavior.

To describe the behavior of the individual drivers, their command of driving and to determine their levels of perception, a number of parameters were introduced, namely desired speed, want for safety and reaction times in different driving situations. In order to cover the whole range of drivers’ behaviors, the single parameters of the model are standardized around a median (normal distribution) (Ludmann, Neunzig & Weilkes).

The model considers four different scenarios that a driver might find themselves in, determining their behavior: 1) uninfluenced driving where the driver is undisturbed by other vehicles and deviates around their average desired speed, 2) approaching where the driver nears the vehicle in front and slows down in order to adjust their speed to match that vehicle and keep their desired safe distance, 3) breaking to avoid an accident where the driver breaks more severely if the distance to the leading vehicle falls below a minimum, and 4) following or ‘unconsciously influenced driving’ where the driver follows the vehicle in front inattentive to their own speed when desired distance is reached and “a limited command of the acceleration pedal, e.g. due to lack of concentration, leads to distance variations between the minimal distance and the maximal following distance according to the respective speed” (Ludmann, Neunzig & Weilkes). The following diagram illustrates this model of a driver’s approaching and following behavior.
This chart illustrates the inefficiency of human following behavior. The following driver accelerates until it reaches a minimum desired distance for safety and then decelerates until the maximal following distance is reached and the cycle continues.

Following behavior follows this pattern because humans tend to “zone out” when they are in following mode, and to overreact to changes in following distance. Autonomous vehicles are constantly aware of speed and exact following distance and are not ruled by human emotions, so they react by making smaller and more gradual, and therefore more fuel and space efficient, changes. The Enhanced Intelligent Driver Model to Access the Impact of Driving Strategies on Traffic Capacity by Arne Kesting, Martin Treiber, and Dirk Helbing of the Institute for Transport & Economics at TU Dresden in Germany explores the contrast between human driving behavior and adaptive cruise control functions and their implications on traffic congestion. In order to make quantitative comparisons, the authors use the Intelligent Driver Model (IDM) to characterize human driving behavior and estimate a new model for the behavior of a vehicle using adaptive cruise control (ACC) through the use of a constant acceleration heuristic. The original Intelligent Driver Model, established by Treiber and others in
2000, combines a free-road acceleration strategy characterized by desired speed $v_0$, maximum acceleration $a$, and $\delta$, the exponent which characterizes how acceleration decreases with velocity and a deceleration strategy which comes into effect when the gap to the leading vehicle $s$ is not significantly larger than the desired ‘safe’ gap $s^*$ (Kesting, Treiber & Helbing 2009). The continuous function for IDM acceleration is as follows:

$$a_{\text{IDM}}(s, v, \Delta v) = \frac{dv}{dt} = a \left[ 1 - \left( \frac{v}{v_0} \right)^\delta - \left( \frac{s^*(v, \Delta v)}{s} \right)^2 \right],$$

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}}.$$  

(Kesting, Treiber & Helbing 2009)

Because the breaking term of the IDM is designed to avoid accidents in the worst case scenario, (i.e. when the leading vehicle breaks at maximum deceleration), “there are situations, characterized by comparatively low velocity differences and gaps that are significantly smaller than the desired gaps, where this worst-case heuristic leads to overreactions” (Kesting, Treiber & Helbing 2009).

In order to extend this model to the behavior of adaptive cruise control systems, the authors introduce a constant acceleration heuristic (CAH) which assumes that the accelerations of the leading and following vehicle will not change in the relevant future (a few seconds), no safe time headway or minimum gap distance is necessary, and drivers react instantaneously (reaction time is zero). This heuristic gives a maximum acceleration $a_{\text{CAH}}$ possible without inducing a crash:

$$a_{\text{CAH}}(s, v, v_1, a_1) = \begin{cases} \frac{v^2 a_1}{v_i^2 - 2s a_1} & \text{if } v_i(v - v_1) \leq -2s a_1, \\ \tilde{a}_l - \frac{(v - v_1)^2 \theta(v - v_1)}{2s} & \text{otherwise}, \end{cases}$$

(Kesting, Treiber & Helbing 2009)
This heuristic is not comprehensive enough to directly model the acceleration of ACC vehicles but is a useful indicator in determining when the IDM leads to decelerations that are unrealistically high for ACC vehicles. The proposed ACC model makes the following assumptions: ACC acceleration is never lower than IDM acceleration; if the IDM and CAH produce the same acceleration the ACC will have that same acceleration; if IDM produces extreme deceleration while CAH produces acceleration greater than \(-b\) (the comfortable level of deceleration) it is considered a mildly critical situation and ACC is the comfortable deceleration plus a fraction \((1-c)\) of IDM deceleration; if IDM and CAH both produce acceleration significantly below \(-b\) it is a seriously critical situation and ACC must not exceed the maximum of the IDM and CAH accelerations; and finally, ACC must be a continuous and differentiable function of the IDM and CAH acceleration models (Kesting, Treiber & Helbing 2009). The resulting ACC model for acceleration is given by:

\[
a_{\text{ACC}} = \begin{cases} 
a_{\text{IDM}} & a_{\text{IDM}} \geq a_{\text{CAH}}, \\
(1 - e) a_{\text{IDM}} + e \left[ a_{\text{CAH}} + b \tanh \left( \frac{a_{\text{IDM}} - a_{\text{CAH}}}{b} \right) \right] & \text{otherwise}.
\end{cases}
\]

(Kesting, Treiber & Helbing 2009)

The authors describe the real world, qualitative implications for this model saying,

Notably, the ACC model leads to more relaxed reactions in situations in which the IDM behaves too conservatively. In contrast to the IDM, the acceleration depends not only on the gap to and the velocity of the leading vehicle, but (through \(a_{\text{CAH}}\)) on the acceleration \(a_l\) of this vehicle as well. This leads to a more defensive driving behavior when approaching congested traffic (reaction to ‘breaking lights’), but also to a more relaxed behavior in typical cut-in situations (Kesting, Treiber & Helbing 2009).

This evaluation is consistent with the actual behavior of adaptive cruise control equipped vehicles. Their defensive driving behavior, fast reaction time and relaxed behavior allow them to drive more efficiently than humans.
Having developed a quantitative model for ACC acceleration, the authors proceed to compare the reaction of ACC vehicles to that of an intelligent driver as modeled by the IDM. The following plots illustrate distance from the leading vehicle, velocity and acceleration in the ‘mildly critical’ event of a lane change directly in front of the vehicle.

![Graphs showing distance, velocity, and acceleration over time for IDM and ACC vehicles.](image)

Based on these plots, it is apparent that the ACC vehicle has a much more relaxed reaction than a human driver. The ACC model results in a deceleration of only 2m/s², not exceeding the maximum comfortable deceleration, while the IDM model produces the assumed maximum deceleration physically possible in the model (8m/s²). Furthermore, “in spite of the more relaxed reaction, the velocity drop of the ACC vehicle is slightly less than that of the IDM (minimum velocities of about 69km/h and 68 km/h, respectively)” (Kesting, Treiber & Helbing 2009).

Because “both the maximum deceleration and the velocity drop are measures for the perturbations imposed on following vehicles,” the difference in driving behavior between the IDM model and the ACC model has serious implications for traffic congestion (Kesting, Treiber & Helbing 2009). To demonstrate this fact the authors examine the impact of the number of ACC equipped vehicles on the road. For one, they
find that the maximum free flow of traffic increases with an increased proportion of ACC vehicles on the road.

![Figure 5.11 (Kesting, Treiber & Helbing 2009)](image1)

These charts show that with 20% ACC vehicles, a 7% increase in maximum free flow can be expected, and with 50% ACC vehicles, a gain of 16% to 21% in maximum free flow could be seen. “Although this appears to be a relatively small enhancement, one should not underestimate its impact on the resulting traffic dynamics. The authors, for example, have shown that an ACC proportion of 20% can often prevent (or, at least, delay) a breakdown of traffic flow” (Kesting, Treiber & Helbing 2009). Furthermore, “comparing this to the reference simulation without ‘intelligent’ ACC-equipped vehicles, individual travel times may vary by a factor of 2 or 3 at least, sometimes even more” (Kesting, Treiber & Helbing 2009). The authors also examine the scenario of traffic flow after a breakdown has occurred. In this case they find that dynamic capacity, or the outflow of a traffic jam, increases with the proportion of ACC equipped vehicles involved:

![Figure 5.12 (Kesting, Treiber & Helbing 2009)](image2)
The increased outflow provided by ACC vehicles allows for traffic jams that do occur to clear up at a faster rate which is also paramount in reducing congestion. All in all, Kesting, Treiber and Helbing find that a 1% increase in adaptive cruise control vehicles translates into an overall increasing in roadway capacity of about 0.3% and this sensitivity is magnified when we consider travel times during breakdowns in traffic flow.

The work of Kesting, Treiber and Helbing is extremely applicable to the congestion benefits of autonomous vehicles because their impact on traffic flow would be essentially the same as that provided by vehicles with adaptive cruise control. A Shared Autonomous Taxi system would innately reduce congestion because its implementation would automatically increase the number of efficiently driven vehicles on the road. Simultaneously, the system would further reduce congestion with its promotion of ridesharing. In 2009, the average vehicle occupancy was 1.59 (U.S. Department of Energy 2010). If that number were simply increased to 2, which should be easily accomplished by Shared Autonomous Taxis, 79.5% less cars would be needed to move the same number of people on roadways. Between increasing capacity with autonomous vehicle driving behavior and decreasing the number of vehicles on the road through ridesharing, a Shared Autonomous Taxi system has the potential to completely dissipate traffic congestion.
Chapter Six
Conclusions and Further Research
The automobile is far and away the most dominant form of transportation in society today. It offers comfort, convenience, speed and reliability that no other mode comes close to rivaling. Nothing compares to the door to door, nonstop, on demand service provided by private automobile ownership. The problem is, as automobile dependence has grown over the years, the negative consequences associated with this mode of transportation become more apparent and more detrimental. Concerns of energy consumption, environmental health, congestion and safety associated with the conventional automobile-based transportation system that is so heavily relied upon make it suboptimal despite the benefits of convenience and comfort that it offers. Nevertheless, increasing awareness of these negative consequences has not yet reduced societal dependence on the automobile. There simply is no existing alternative that comes close enough to competing with the efficiency and ease of the automobile to deter from its use—even considering all of the negative consequences associated with it. Any benefits that existing alternative systems may offer in terms of lowering pollution, reducing congestion, and improving safety are negated by their inability to come even close to reaching the convenience and comfort of the automobile. Public transportation is an example of an alternative to the automobile whose implementation of ridesharing could have the potential to reduce congestion, but given that it runs on a predetermined route and schedule, it comes nowhere near the level of convenience provided by the automobile and thus goes unused by most. Another attempt at creating an alternative to the conventional automobile can be seen in the development of vehicles like hybrids and electric cars. But while these vehicles may be helpful in reducing energy consumption and environmental impact, and even preserve the convenience and comfort of the automobile, they do nothing to ease congestion or increase safety. What is really needed in order to break the automobile addiction is a completely new, easily implemented transportation system that provides the same level of convenience as the automobile but simultaneously combats all of the negative consequences associated with automobile use.

One alternative system that has the potential to overtake the automobile by addressing all of the problem areas while still preserving fairly comparable convenience and comfort is Personal Rapid Transit. However, though there are a few test tracks in existence, it has become clear that the cost of infrastructure is a major, possibly
insurmountable obstacle that not only stands in the way of implementing initial test systems, but also in further expanding such test systems into a widespread transportation system that could make a significant difference. This is where the newly developing technology of autonomous cars could make a difference. The development of autonomous vehicles would make a system similar to PRT possible on our existing roadways, side stepping the hurdle of expensive infrastructure. And even on the level of individual use, autonomous cars begin to address most of the issues associated with automobile use. As autonomous vehicle technology begins to develop, the outlook for revolutionizing the current transportation system and breaking the automobile addiction becomes more hopeful.

The development of autonomous vehicles is already well underway. Even commercially sold vehicles driven by the masses are gradually shifting toward autonomy with features like cruise control and adaptive cruise control, collision avoidance, lane following, blind spot monitoring and self-parking systems. It is only a matter of time before the last leap to full autonomy is made. Companies, Universities and researchers around the globe are already racing to build the first and the best autonomous car. The vehicles being developed use a variety of cameras, lasers and sensors to obtain a comprehensive understanding of the state of the world surrounding the vehicle at every instant. On board computers take in all of this data, then determine and execute the proper course of action without any human input. Some of the leading efforts that have been discussed are those by Google, BMW in Germany, VisLab in Italy, Carnegie Mellon, Virginia Tech and Princeton PAVE. And the test vehicles are well on their way to becoming reliable enough to operate on public roadways; in fact, Google’s fleet of automated Toyota Priuses has already driven over 190,000 miles on California highways (Guizzo 2011).

Autonomous vehicle technology presents many exciting new possibilities for transportation. Computer operated vehicles outshine human operated vehicles both in efficiency and safety. The truth of the matter is that computers can gather and keep track of more information than humans can. They can also think and react much faster which makes them much more accurate and efficient when it comes to driving. Because of this, keeping all else equal and simply switching from human operated cars to autonomous
vehicles could immediately lower energy consumption, lessen environmental impact and ease congestion. Autonomous cars operate in a much more fuel efficient manner than humans who burn excess gasoline with excessive acceleration, deceleration and braking. And the accuracy and quick reaction time of autonomous cars allows them to safely drive with reduced spacing making more efficient use of road space, and at higher speeds which keeps traffic moving. Basically, the benefits reaped by autonomous vehicles are a result of removing the human element of driving—and the safety benefits are no exception. As has been discussed, most traffic accidents result from human error, and autonomously operated vehicles remove the human from the equation which would reduce the number of traffic accidents. Roadways would be much safer if they were filled with autonomous cars rather than cars operated by distracted, drowsy and unpredictable human drivers.

Despite the clear benefits of autonomous vehicle technology, there are several social, psychological and legal obstacles to overcome before it becomes widely accepted and adopted, even once the technology is thoroughly tested for reliability. One of the factors to consider is societal attachment to the automobile. The majority of this attachment seems to revolve around the freedom and mobility associated with the automobile, which would be completely preserved, and even increased for those who do not have the ability to drive, with autonomous cars. Another small piece of this attachment which autonomous cars might disrupt is driving enjoyment. But given that in this day and age, affinity for technology and the internet seem to trump love of driving, this hurdle should be easily overcome when people realize that self driving cars would allow them to be on their phone, iPad, or laptop during their commute; and most people would choose that over driving. Furthermore, autonomy is simply an extra feature; a person can still opt to drive their own vehicle if they feel the urge to drive. Another key obstacle to the acceptance of autonomous vehicles, both socially and legally, is safety. But as has been discussed, the informational capacity, fast reaction time, and consistency of computers makes autonomous cars much safer than those operated by humans. And while it may take society some time and evidence of autonomous cars functioning safely and reliably to get used to that thought, the issue is starting to be addressed by some state legislatures to allow for this to happen. A handful of states have officially legalized the
testing of autonomous cars on their state roads, and the Nevada Department of Motor Vehicles has put into effect a slew regulations and restrictions in order to address and manage safety concerns. The Nevada DMV even addresses liability issues regarding the operation of autonomous vehicles without a driver present in the car, acknowledging that this is the future of autonomous vehicles. As the transition is made toward that point technologically and socially, legislation will have to keep up and address the questions of liability that are sure to surface as the responsibility of driving shifts from human drivers to the cars themselves. It may take some time for this to happen as autonomous cars become more reliable and society becomes more comfortable with the technology. The transition is sure to be drawn out and complicated, but it is necessary for autonomous cars to be allowed to operate without a human driver in order for them to reach their full potential as a revolutionary transportation system.

The development of autonomous vehicle technology allows for the opportunity to truly revolutionize the existing, automobile-dependent transportation system. Simply replacing the conventional human-operated automobile with autonomous cars would provide a plethora of benefits in terms of safety, fuel efficiency, environmental impact, and reduced congestion due to the fact that computer-operated vehicles can collect and process much more information than human drivers, have much faster reaction times, and are not influenced by distractions or human emotions. These characteristics make them much safer and more efficient than human drivers. And this sort of one-to-one substitution of autonomous vehicles for human operated vehicles is a logical first step of implementation for the technology. It allows society to become comfortable with the idea of a self-driving car while still feeling in control as they sit in the driver’s seat. This should allow for a smooth transition toward allowing autonomous vehicles to operate on their own, completely unmanned. It is difficult to say when social norms and legislation will catch up to the technology, but when they do, the true potential of autonomous vehicle technology can be exploited.

When autonomous cars become integrated into society at a level where they can drive around unoccupied, their true potential can be tapped by completely rebuilding the transportation framework with a Shared Autonomous Taxi system. Autonomous vehicle technology allows for the implementation of a Personal Rapid Transit-like system, but
without the need for extensive infrastructure as the cars can operate on existing roadways. All a passenger has to do is walk to the nearest taxi stand, input their destination and briefly wait to be picked up by their taxi which will be shared by passengers travelling along a similar route as determined by the underlying computer system. Or, a passenger can pay a premium to be picked up at their doorstep and then be transported in the same way. A system like this would enable ridesharing among the mass of similar routes travelled during peak hours and thereby significantly reduce rush hour congestion. During off peak hours, the probability of similar trips is much smaller. But since congestion is not a problem, it doesn’t matter if it is unable to promote much ridesharing. The system would operate as a door-to-door taxi, where the vehicles are able to drive themselves from one drop-off location to their next pick up. Essentially, a Shared Autonomous Taxi System would completely remove the need to own an automobile—a necessity in our current transportation situation.

The potential ability of Shared Autonomous Taxis to alleviate congestion by promoting ridesharing during peak hours is demonstrated in the preceding analysis of detailed travel demand in Mercer County, New Jersey. The simplified system, modeled in Chapter 5, of uniformly distributed taxi stands, accessible to all travelers by a quarter mile or less walk, demonstrated how a Shared Autonomous Taxi stand could serve the distribution of trips throughout the county. Even with the simplified, suboptimal designation of taxi stand locations it was found that the average trips served by each stand would be 127.2988 with a maximum of 22,926 trips served by the taxi stand located in Princeton, New Jersey. Upon closer examination of this large taxi stand, it also became clear that the distribution of trips throughout the day would allow for significant ridesharing as there is a high volume (20 to 70 arrivals to the taxi stand per minute) during peak hours in the morning and the evening. This highly simplified model illustrates the potential congestion relief that could be achieved by a Shared Autonomous Taxi system. However, there is still significant further research to be done in implementing an optimal system. For one, the location of taxi stands should be determined based on analysis of travel demand consolidation rather than by a uniform distribution so that the system can effectively serve the highest number of trips possible and have a higher average number of trips served by each taxi stand. An analysis of
vehicle occupancy based on wait time must also be examined in order to determine what the optimal wait time for departing vehicles should be, with a goal of maximizing vehicle occupancy without making passengers wait too long for potential ride sharers. Finally, once the location of taxi stands has been determined and wait time analysis has been performed, the travel demand throughout the day at each taxi stand must be analyzed in order to estimate how many vehicles are needed to support the system and how they should be dispatched to serve each taxi stand.

Autonomous vehicle technology may be the key to revolutionizing our current, automobile dependent transportation system.

A properly designed urban people mover system based on light single occupancy vehicles has numerous advantages. In the U.S. alone it could save thousands of lives annually and free billions of dollars spent on caring for victims of traffic accidents. Its convenience could surpass the automobile and provide mobility to people who are unable to drive. It can reduce urban congestion and the sprawl caused by parking lots. Wide scale acceptance could reduce U.S. oil consumption by 16% and eliminate 146,000 metric tons of carbon daily (Folsom 2011).

Shared Autonomous Taxis perfectly fit the bill of a system that could have this kind of impact. What makes the Shared Autonomous Taxi system a truly viable alternative for the automobile is that it provides the same level of convenience and comfort that society demands, and which most other alternatives have been unable to achieve. In fact, it actually surpasses the conventional automobile in that it does away with the hassle of maintenance associated with car ownership, including parking and storage, and it provides accessibility to those who can’t drive their own car. Furthermore, it addresses every single one of the issues associated with automobile dependence. Autonomous vehicles are much safer and drive in a much more fuel efficient manner; therefore they reduce both energy consumption and environmental impact. And their driving efficiency, paired with the ridesharing promoted by Shared Autonomous Taxis, would significantly if not completely dissipate traffic congestion, a growing problem in our automobile dependent world. Finally, and most importantly, now that autonomous vehicle technology development is underway, implementation is fairly straightforward and
affordable since the cars can drive on existing roadways. All in all, the Shared Autonomous Taxi system proposed in this thesis is an ideal alternative to today’s preferred mode of transportation—the privately owned automobile—because it provides safer and more efficient transportation, lessens environmental impact, reduces congestion through the promotion of ridesharing and utilizes existing infrastructure, all while providing a level of convenience and comfort superior even to that of the private automobile.
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