Executive Summary

1 Introduction

New York City (NYC) would like to implement a fleet of autonomous vehicles (AV) by 2020 as part of a larger initiative of establishing itself as a world leader in smart city infrastructure. AV is a fledgling technology that has seen tremendous advances in recent years involving big technology players such as Google and Uber. An AV vehicle is equiped with GPS, radar sensors and computer processors which enable it to drive itself without the need of human interaction. Because of the novel nature of AV technology, there is a considerable amount of uncertainty regarding the impact of its implementation on traffic issues including safety, congestion, energy consumption and environmental impacts. NYC officials wish to study potential alternatives and determine their effect, while considering uncertainty, on these outcome and optimal strategies moving forward with AV technology within the NYC fleet of vehicles. This study will focus on the alternatives available to implement this technology from AutoMerge, Inc. (AM) specifically in NYC's 40-passenger transit buses. It will compare different alternative strategies by performing a Benefit Cost Analysis (BCA) to assess how these different options impact the general population of NYC, which are the main stakeholders in this issue. Among the factors to be included in the analysis are: safety, energy consumption, air pollution, GHG emissions, weather conditions and time savings due to improvement in traffic flow. Section 2 presents a detailed description of the problem and the alternatives analyzed. Section 3 presents the analysis of each alternative and the results found. In section 4 a sensitivity analysis is performed for some inputs. Section 5 discusses the results of the analyses and section 6 presents the conclusion and recommendations of this study.

2 Problem Description

2.1 Alternatives

Broadly, NYC must consider the following three alternatives.

Alternative 1: Do not implement AV.

This is the reference alternative. AV is not implemented and the benefits and costs are the ones already incurred to the population. There is relatively little uncertanty associated with this outcome because there is historical data to project the effect of this alternative on outcomes.

Alternative 2: Implement AV in the NYC bus fleet.

In this alternative, the city implements the AV technology in the bus fleet directly (without performing any pilot tests). Because this is an emerging technology, it is unclear how AV will perform in each outcome so uncertainty analysis will help determine the expected value for each outcome using the risk information currently available.

Alternative 3: Perform a pilot test with an amount of n buses before deciding to implement AV.

In this alternative, the city performs a pilot test with a predefined amount of n buses. The pilot test has an associated cost directly proportional to n. The potential benefit of running a pilot study is the additional information gained on risks associated with congestion and other outcomes. With this additional information resulting from the test, NYC can make a better informed decision whether or not to invest in AV technology.

2.2 Benefits & Costs

Although public transit systems are essential to any urban area, they also incur several costs to the general population. Implementing AM in the bus system will impact these costs in different ways.

1. **Capital and Operating Costs of implementing AM.** The most obvious costs are the capital and operating costs of implementing and operating the AM system in the buses. Ordinary capital and operating costs related to the bus operation will not be considered in this analysis since they will be incurred in all alternatives. Estimates for capital and O&M costs for the AM system were informed in a per bus basis, conditioned on the age of the bus. We used this data to compute these costs.

Table 1: Capital and O&M costs of the AM system

	Variable	Value	Notes
(a)	# buses with age $<$ 5 years	2313	Source: [6]
(b)	# buses with age 5-9 years	1296	Source: [6]
(c)	# buses with age 10-20 years	1437	Source: [6]
(d)	Capital Cost per bus age $<$ 5 years	$ 5000	Source: [6]
(e)	Capital Cost per bus age 5-9 years	$ 6500	Source: [6]
(f)	Capital Cost per bus age 10-20 years	$ 8500	Source: [6]
(g)	**Total Capital Cost**(*)	**$ 45.7 Million**	**=(a)*(d)+(b)*(e)+(c)*(f)**
(h)	Annual O&M Cost per Bus	$ 1500	Source: [6]
(i)	**Total Annual O&M Cost** (**)	**$ 7.6 Million**	**=[(a)+(b)+(c)]*(h)**

(*) Capital costs are considered to be incurred only in the first year

(**) O&M costs begin to occur in the fifth year of the analysis (when AM starts operating)

2. **Traffic Congestion.** Being a part of the transit system, buses have an impact in the traffic congestion of NYC. This traffic congestion incurs in a social cost due to longer commutes, wasted hours for the general population and additional fuel consumption. The use of AM can have an impact in the traffic flow and potentially decrease these costs. To calculate congestion costs, we only consider this cost related to bus commutes

(since we assume that these will be the ones impacted by AM). Table 2 presents the computation of the traffic cost for the reference case

Table 2: Estimate of social costs due to traffic congestion in NYC

	Variable	Value	Notes
(a)	Annual Cost per Commuter	$ 1739	Source: [8]
(b)	Annual hours in congestion per commuter	74 hours	Source: [8]
(c)	Cost per minute	$ 0.39	$(a)/[(b) * 60]$
(d)	Total person trip per day	1.52 million	Source: [7]
(e)	Average time in daily person trip	49 minutes	Source: [7]
(f)	**Total annual congestion cost**	**$ 10.5 Billion**	**=360*(e)*(d)*(c)**

3. **Fatalities & Injuries.** Another cost are traffic related injuries and fatalities. Using AM in the bus system can have an impact in traffic safety and decrease these costs. The cost of each death is estimated using the standard Value of Statistical Life (VSL in $). The cost of each injury was estimated using data from CDC for injuries costs for each type of victim (motorist, passenger, pedestrian, etc.). Using historical data of number of mortalities and injuries in transit accidents in NYC, we computed total cost of traffic mortalities. Table 3 present these costs.

Table 3: Estimate of social costs due to traffic mortalities and injuries in NYC

	Variable	Value	Notes
(a)	VSL (2015 $)	$ 8.7 Million	Source: [1]
(b)	Number of fatalities per year	16	Source: [7]
(c)	**Total annual mortality cost**	**$ 150 Million**	**=(a)*(b)**
(d)	Average Cost of Injury	$ 179,000	Source: [2]
(e)	Number of injuries per year	1740	Source: [7]
(f)	**Total annual injury cost**	**$ 311 Million**	**=(d)*(e)**

4. **Emissions.** Another major external cost of the bus system is the one related to the emission of air pollution gases and greenhouse gases. These emissions result in major health hazards for the general population and can affect future climate. Implementing AM can have an effect of changing these emissions by improving traffic flow. Because at this point we have emission data available only for buses, we focused our emission cost estimate only on buses. Table 4 presents the computations of these costs.

   We assume that improvements from AM will only affect emissions as a result of changes in travel idle time (i.e., as congestion decreases, vehicles spend less time in idle status but still travel the same distance).

Table 4: Estimate of social costs due to emission of air pollutants and GHG from NYC buses

	Variable	PM	NO_x	GHG	Notes
(a)	Running Emission Factor	0.172 g/mile	17.2 g/mile	3659 g/mile	Source: [5]
(b)	Marginal Cost of emission	1.27 $/g	0.07 $/g	30 $/ton	Source: [4], [3]
(c)	Total annual vehicle miles traveled	700 million miles			Source: [7]
(d)	**Total annual running emission cost**	**$ 153 Million**	**$ 839 Million**	**$ 77 Million**	**=(a)*(b)*(c)**
(e)	Idle Emission Factor	0.04 g/min	1.109 g/min	NA	Source: [5]
(f)	Total person trip per day	1.52 million			Source: [7]
(g)	Average time in daily person trip	49 minutes			Source: [7]
(h)	Average people in each vehicle	30			Study assumption
(i)	Total annual travel time	893 Million minutes			= (f)*(g)/(h)
(j)	Share of travel time vehicle is idle	0.2			Study assumption
(k)	**Total annual idle emission cost**	**$ 39 Million**	**$ 14 Million**	NA	**=(i)*(j)*(e)*(b)**

2.3 Uncertainty

In addition to the costs listed above, there are also uncertainties associated with the implementation of AM. Three sources of uncertainties are considered in this analysis: the uncertain effect of AM in traffic congestion (and as a consequence in emissions), the uncertain effect of AM in traffic safety (mortalities and injuries) and the uncertain effect of weather in AM operation.

1. **Effect of AM in traffic congestion**

   To represent the uncertainty of the actual effect of implementing AM in the traffic of NYC, we considered three possible outcomes: traffic congestion gets much better (MB), traffic congestion gets a little better (LB) and traffic congestion gets a little worse (LW). Each outcome has a probability associated with it. Table 5 presents the outcomes and the probabilities associated.

2. **Effect of AM in traffic safety**

   To represent the uncertain result in traffic safety of using AM, we used the results of an expert elicitation survey. Five experts gave three possible outcomes for the changes in

Table 5: Possible outcomes in traffic congestion of the implementation of AM (Source: [6])

Outcome	**Commute time change**	**Probability**
Much Better (MB)	235 seconds	0.20
Little Better (LB)	55 seconds	0.40
Little Worse (LW)	30 seconds	0.40

traffic safety: a lower bound, a best estimate and an upper bound. We took the median value of each outcome and assigned a probability of 80% to the best estimate value and 10% for each of the two other values. Table 6 presents the outcomes and the probabilities associated.

Table 6: Possible outcomes in traffic safety of the implementation of AM (Source: [6])

Outcome	**Change in Mortality**	**Change in Injuries**	**Probability (*)**
Upper Bound (sUB)	-10%	-10%	0.10
Best Estimate (sBE)	-4%	-4%	0.80
Lower Bound (sLB)	+1%	+2%	0.10

(*) The probabilities for each case were assigned by us

3. **Effect of weather in AM operation**

   We assumed that in the event of bad weather the AM system would not be able to operate autonomously and a human driver would need to take manual control of the vehicle. In this case we assumed that the system would operate identically to reference case and hence all results would be the same as alternative 1. Using historical data from NY weather, we estimated the expected frequency that weather may be classified as "Bad". The resulting probabilities are presented in Table @@.

Table 7: Estimated probabilities of "Good Weather" and "Bad Weather" (Source: [9])

Outcome	**Probability**
Good Weather	92%
Bad Weather	8%

2.4 Assumptions

Table 8 present the general assumptions used in this study.

Table 8: General Assumptions

Variable	Value	Notes
Discount rate	5 % per year	Study assumption
Time Horizon	10 years	Study assumption

2.5 Decision Framework

With all the pertinent costs, assumptions and representations of uncertainties we can now analyze the decision of investing or not in AM. Figure 1 shows a diagram of this decision and of the uncertain outcomes associated with each decision. In order to simplify the diagram, we didn't represent Alternative 3 (deciding to make a pilot test before deciding between alternative 1 and alternative 2). It would be a third brach coming out of the decision node and the the result of the test would change the probabilities for each traffic outcome (MB, LB and LW). Hence, after the test result node, there would be an identical diagram as the one represented by Figure 1.

3 Analysis and Results

Table 9 presents the resulting NPV for each alternative. For the reference case (Alternative 1) we can observe that the component that results in the largest cost is congestion. The total present value of costs for the reference case is approximately $ 109 Billion. Implementation of AM (alternative 2) results in a decrease of the expected present value of costs of approximately $ 2 Billion or 1.6%. Most of the reduction is due to reduction in the congestion costs. On the other hand, the component cost that results in the biggest relative change is mortality costs, which are reduced by 3.9 % ($ 60 million).

Table 9: NPV results for Alternative 1 and Alternative 2

Name	Alternative 1 (Billion $)	Alternative 2 (Billion $)	Change (Billion $)	Change (%)
Capital Costs	0	0.05		
O&M	0	0.06		
Mortality	1.45	1.39	-0.05	-3.46
Injury	3.23	3.11	-0.12	-3.71
Congestion	109.12	107.16	-1.96	-1.8
Air Pollution	10.55	10.55	0	0
GHG	0.8	0.8	0	0
Total	125.15	123.12	-2.03	-1.62

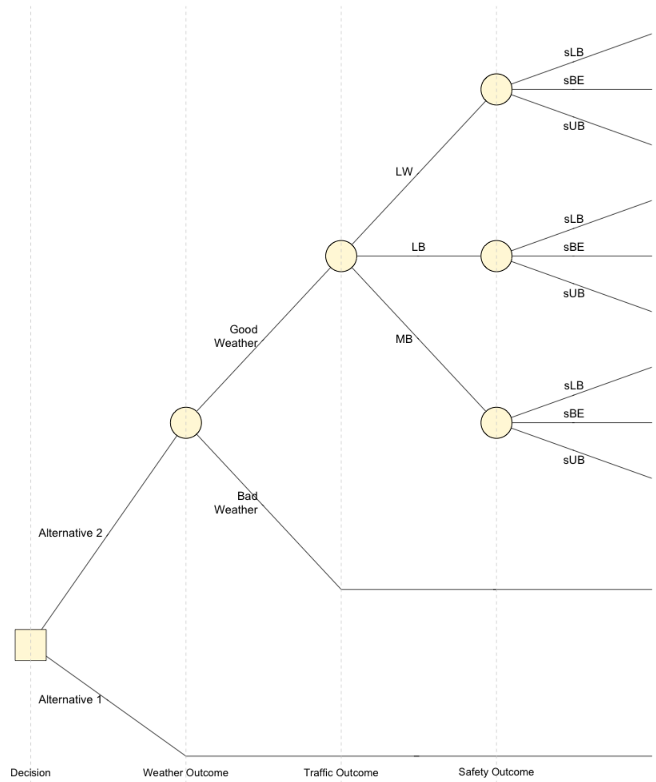

Figure 1: Representation of the problem as a decision tree. The square node represents the decision of choosing either alternative 1 or alternative 2. The circle nodes represent the uncertain events related to weather, traffic congestion or traffic safety. Alternative 3 could be interpreted as another branch in the decision node that would result in a new tree identical to the this one but with different probabilities for MB, LB, LW

To analyze whether choosing Alternative 3 (performing a pilot test) would be better than choosing Alternative 2 (which we already know is better than Alternative 1 without the test), we can compute the Net Expected Value of Imperfect Information (NEVII). This quantity would show the monetary value of this pilot test and already accounts for the actual cost of the test. Figure 2 presents the NEVII for different values of the test size. We can observe that for small sizes of the test ($< 50\%$ of the fleet), it aggregates no value to the decision maker. This means that the expected value of the decision with the test is the same as without the test (i.e., choosing alternative 2). As the test size increases, the value also increases, which means that the NPV with the test is larger than the NPV without the test. According to these results, the optimal test size is 100% of the fleet.

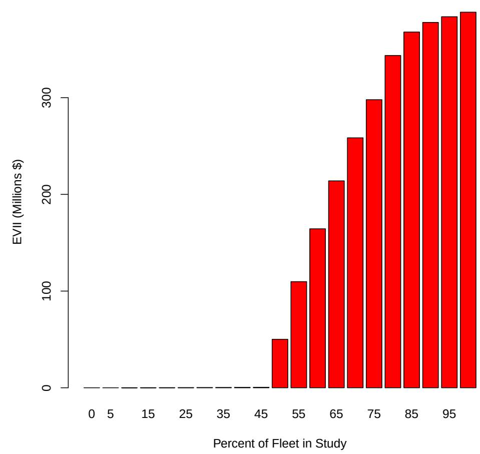

Figure 2: Net Expected Value of Imperfect Information

4 Sensitivity Analysis

To perform the sensitivity analyses, we followed the methods used above but varied key assumptions used in the original computation of net expected values under uncertainty. We varied the discount rate from 2 to 12% simply because these are the extreme values for this figure. While alternative 3 was the best choice under all discount rates, the net expected NPV varied greatly under differing discount rates. Similarly, alternative 3 had the least net expected cost under all values used for lifetime and VSL. All ranges considered were from half to double the value chosen in the main analysis or expanded to a wider range if reasonable values exceeded this range. We also explored the effect of congestion cost per person on NPV but found similar results: alternative 3 was robust to all values chosen. Last, weather affected alternatives 2 and 3 but not 1. As the percent of weather undrivable for AM increases, it becomes less cost effective; however, without weather patterns changing dramatically (precipitation more than 50 of the time) alternatives 2 and 3 will continue to cost less than alternative 1.

5 Discussion

6 Conclusion & Recommendations

[1] U.S. Environmental Protection Agency. *Guidelines for Preparing Economic Analyses*. Tech. rep. 2010. URL: http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf.

[2] Centers for Disease Control and Prevention (CDC). *Data & Statistics (WISQARS) Cost of Injury Reports*. URL: https://wisqars.cdc.gov:8443/costT/cost_Part1_Intro.jsp.

[3] U.S. Energy Information Administration (EIA). *EASIUR Online Tool*. URL: http://barney.ce.cmu.edu/~jinhyok/easiur/online/.

[4] U.S. Energy Information Administration (EIA). *The Social Cost of Carbon*. URL: https://www3.epa.gov/climatechange/EPAactivities/economics/scc.html.

[5] U.S. Environmental Protection Agency (EPA). *Average In-Use Emissions from Urban Buses and School Buses*.

[6] AutoMerge Inc. *Memorandum*. date of document: 22 December 2015.

[7] AutoMerge Inc. *Summary of New York City Transit Data*.

[8] Texas A&M Transportation Institute. *Urban Mobility Information*. URL: http://mobility.tamu.edu/ums/.

[9] Rain or Shine Inc. *New York City Weather Excel file*. date of document: 28 December 2015.

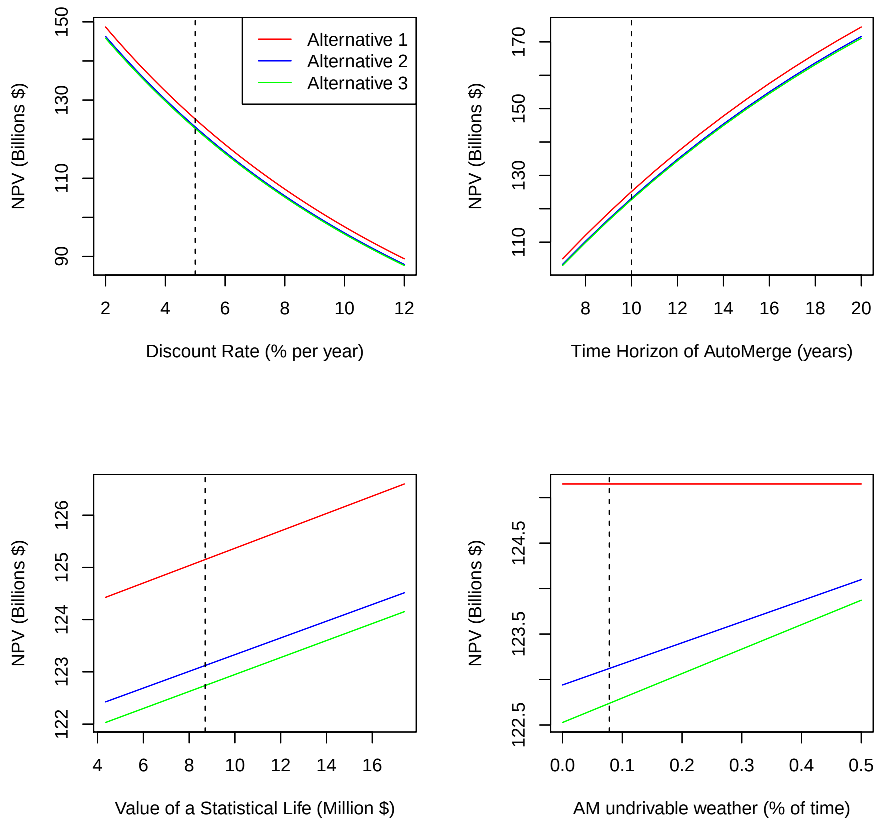

Figure 3: The figure above shows the impact of discount rate, lifetime of AM, value of a statistical life, and weather conditions on expected net NPV. The vertical dashed line indicates our assumptions from the main analysis