Term Project **TJ Liggett, Izzy Sommers**
MATH 327 Teammates: TJ Liggett, Izzy Sommers
Prof. Olimb Due Date: 05/15/20

Dear Governor,

We are writing to you to give you insight about how autonomous vehicles can be used in the Seattle area in the future to best optimize traffic flow. The research paper following this letter will give further details into our results. Our recommendation at this time is that a switch to all autonomous vehicles would be the most efficient option. Our research shows that in doing so traffic overflow could be cut almost in half.

While we know this may be unreasonable financially, a steady integration of self-driving vehicles will continually increase traffic flow efficiency. Our research shows that there is a negative linear relationship between autonomous vehicle penetration and the percentage of overflow traffic. As autonomous vehicle penetration increases, the percentage of traffic overflow will decrease. Reducing traffic overflow will decrease traffic congestion and increase the flow of traffic in the area. This will lead to higher traffic speeds and lower commute times. Our research also showed that this linear relationship means there is a steady decrease of traffic flow with the introduction of self-driving cars. There is not a specific tipping point where there is a more significant impact. Therefore, the increase in efficiency will be the same for each level of autonomous integration. It is also important to note that dedicating specific lanes to autonomous vehicles did not yield different results than randomly integrating self-driving cars into all lanes.

Overall, introducing self-driving cars to the Greater Seattle area will be an effective way to decrease traffic congestion. Converting to all autonomous vehicles will have the greatest increase on traffic flow efficiency. The research paper attached to this letter will give further details on how we reached this conclusion.

Sincerely,

TJ Liggett and Izzy Sommers

Executive Summary

This project comes from a prompt in the 2017 MCM Contest listed as Problem C: "Cooperate and Navigate". The goal is to model the traffic flow in one area of Seattle and come to a conclusion about how the integration of self-driving vehicles would change the efficiency of the highways.

Our data covers the Seattle counties of Thurston, Pierce, King, and Snohomoish counties and specifically data on highways 5, 90, 405, and 520. Our data contained lane amounts each direction and average daily traffic counts for each section of highway. We combined this knowledge with what we learned about about the impact of autonomous vehicles in our research. Our research measures the impact of self-driving at different levels of autonomous integration. This includes two separate analysis routes; switching a percentage of all vehicles over to self driving cars and switching an amount of lanes to autonomous vehicles. We looked into both ideas in this paper. Lastly, we wanted to identify if their was a specific point of autonomous integration that made a unique, significant impact on traffic flow. The main goal of this project is to get an understanding of these metrics to advise how the integration of autonomous vehicles could best be used in the Greater Seattle area.

Background/Theory

The research for this project focused on three different traffic simulation categories; microscopic, mesoscopic and macroscopic. Microscopic approaches focus on individual vehicles. The main metrics studied are individual vehicle's velocity, speed, driver behavior and location. A Macroscopic view sees the bigger picture by looking at traffic flow as a whole. The most common metrics used for macroscopic are traffic density, distribution of vehicles, and general flow of traffic. Mesoscopic methods combine the methods of both microscopic and macroscopic concepts[1, p. 123].

Another important piece of our research focused on Free Flow Speed or FFS. FFS is a vehicle's possible speed if it was the only vehicle on the road. It can also be described as the vehicle's desired speed because it is unaffected by its environment. Free Flow Speed is a common way to estimate highway capacity. A standard flow rate can be calculated based on the free flow speed. The flow rate is the maximum number of vehicles that can be on the road while all vehicles are at free flow speed. Free flow speed is measured in miles/per hour and flow rate is usually expressed in vehicles/hour/lane [2, pg. 36]. Shown below is a figure from "Traffic Data Computation Method" showing standard comparison of Free-Flow Speed to Flow Rate. In our research, the speed limit is 60 mph. This means we will assume a Free-Flow Speed of 60 mph and therefore, a flow rate of 1600 pc/h/ln.

Free-Flow Speed (mph)	Flow Rate (pc/h/ln)
75	1,150
70	1,300
65	1,450
60	1,600
55	1,750

Figure 1: Free Flow Speeds and Flow Rates

Assumptions and Justification

As talked about previously, we assumed a Free-Flow Speed of 60 mph based on the highway speed limited listed in the problem statement. Based on the data shown in Figure 1 shown above that found in the source "Traffic Data Computation Method" we also assumed a Flow Rate of 1600 pc/h/ln [2, pg 36].

Next, we looked at research on the impact autonomous vehicles would have on traffic flow. In one resource, "the impact of autonomous vehicles on urban traffic network capacity" researchers classified different possible levels of automation for vehicles. This levels range from fully manual to partial automation to completely autonomous. These different levels can be described in Table 2 shown below.

Level 0 – 'No automation'	'The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems.'
Level 1 – 'Driver Assistance'	'The driving mode-specific assistance system of execution by a driver either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.'
Level 2 – 'Partial Automation'	'The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task.'
Level 3 – 'Conditional Automation'	'The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human drivers respond appropriately to a request to intervene.'
Level 4 – 'High Automation'	'The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene.'
Level 5 – 'Full Automation'	'The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.'

Figure 2: Various levels of autonomous integration of vehicles [3, pg 2]

Because of this, we chose to consider numerous possible scenarios of how autonomous vehicles might be introduced. One way to look at this is to find the percentage of autonomous vehicles out of all the vehicles on the road. We wanted to know how traffic flow efficiency changed based each of these different percentages. These efficiencies will differ because autonomous vehicles and passenger vehicles interact differently with eachother. One metric studied is called mingap. This is the minimum amount of space between two vehicles where conditions are still considered. Autonomous vehicles have a smaller mingap when interacting with other autonomous vehicles. This allows cars to be closer together which increases the maximum flow rate of a given highway. Fully autonomous vehicles can also have greater overall accelerations compared to nonautonomous cars. Human errors caused by drivers are also removed in a fully autonomous system. These are all metrics to show the ways the highway efficiency can be increased with an integration of autonomous vehicles. These different metrics and their effects on traffic were studied in a driver flow model package known as SUMO simulation [3, pg 5].

In the same research project, “The impact of autonomous vehicles on urban traffic network capacity”, the authors furthered their findings from the SUMO simulations. The researchers built a model to approximate average speed based on the proportion of autonomous and non-autonomous vehicles on the road. Then, they used linear regression methods to estimate the relative change in traffic control based on the proportion of autonomous vehicle integration. Their findings can be seen in Figure 3 shown below, which is from their research paper.

AVs penetration rate	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Maximum traffic flow (veh/h)	57,016	57,753	58,511	59,293	60,106	60,958	61,865	62,839	63,881	64,983	66,142
Relative change compared to the zero penetration case	–	1.29	2.62	3.99	5.42	6.91	8.50	10.21	12.04	13.97	16.01

Figure 3: Percentage of autonomous vehicle and comparative impact[3, pg 7]

The second column, relative change compared to the zero penetration case, was valuable to our research. We used these values to understand the percent increase in maximum flow based on the percentage of autonomous vehicles on a highway. Research data also showed the percent increase in efficiency that self driving cars would create. From this data, we analyzed traffic flow to see the impact of self drivings car by the ratio of self-driving cars to human drivers on the road. We looked to see which percentage of self driving cars is optimal.

Methodology and Results

The goal of the research was to measure how rush hour traffic congestion was impacted by the inclusion of autonomous vehicles. Rush hour traffic was calculated from the assumption that 8 percent of traffic occurs during rush hour, as stated in the problem. Comparing rush hour traffic to the theoretical free flow capacity of the highway sections was the base of the research. In areas where traffic exceeds the free flow capacity, we can assume congestion issues will arise. The inclusion of autonomous vehicles in a system will increase the free flow capacity, and push more of the highway sections underneath this free flow capacity as show in Figure 4.

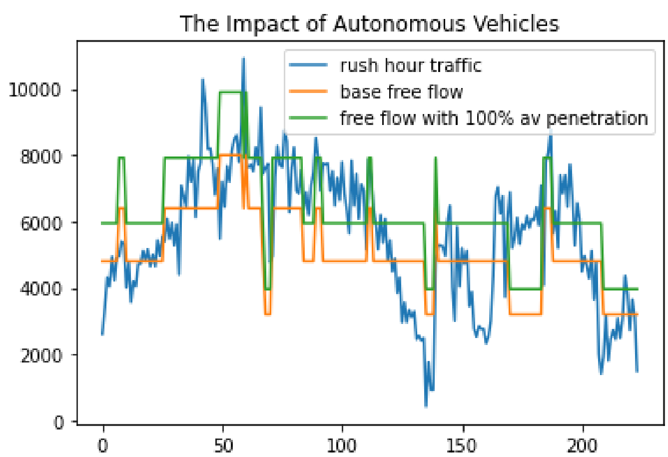

Figure 4: Autonomous Vehicle Penetration Impact on Free Flow Percentage

Two calculations of traffic overflow were used to measure these conditions: the percentage of highway sections that rush hour traffic was over the free flow capacity (overflow percentage) and the sum of vehicles that were above the free flow capacity (overflow sum percentage). These statistics were measured for both the individual highways in each direction as well as the overall system in each direction.

First analysis was done for the impact of autonomous vehicles as a percentage of the total vehicles on the highway. The free flow capacity for each highway section was calculated for various percentages of autonomous vehicle penetration. Overflow percentages as well as overflow sum percentages were then calculated for each highway and the overall system.

Figure 5 shows the impact of autonomous vehicle penetration on overflow percentage. The overall results showed a relatively linear relationship between autonomous vehicle penetration and overflow percentage for both the overall results and Route 5. Overflow percentage showed a steep drop off on Route 405 and Route 90 at 50 percent av penetration. Route 520 saw little impact before 60 percent automation.

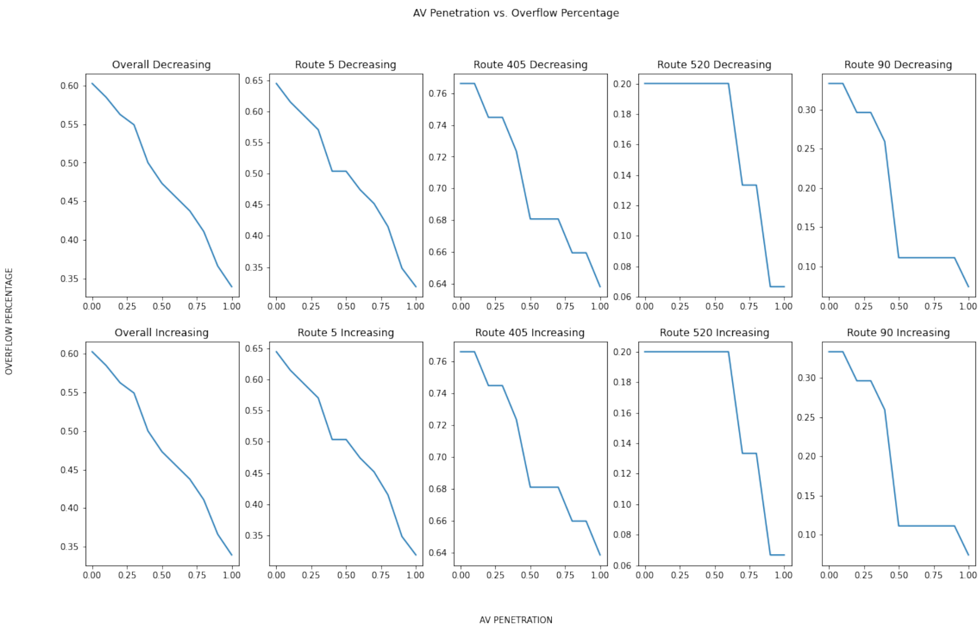

Figure 5: Autonomous Vehicle Penetration Impact on Overflow Percentage

Figure 6 shows the impact of autonomous vehicle penetration on overflow sum percentage. For this measure, a strong linear relationship appeared on all of the routes as well as in the overall results. These results showed a negative correlation between autonomous vehicle penetration and overflow sum percentage.

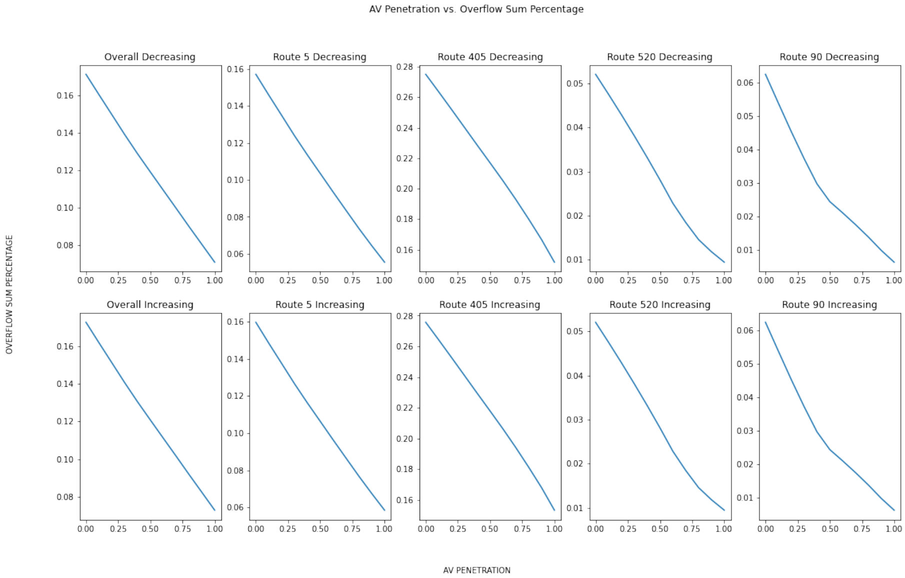

Figure 6: Autonomous Vehicle Penetration Impact on Sum Overflow as a Percentage of Total Traffic

Second analysis was done for the impact of dedicating specific highway lanes to autonomous vehicles. Free flow capacities were calculated by designating a specific number of lanes to autonomous vehicles and changing the capacity of those individual lanes. The same measures of overflow percentage and overflow sum percentage were used for lane analysis.

Figure 7 shows autonomous vehicle lane inclusion versus overflow percentage. This showed a linear relationship for routes 405 and 5 as well as the overall results. Route 520 saw a steep decline with the inclusion of two autonomous lanes, with a lesser decline in the same place for Route 90.

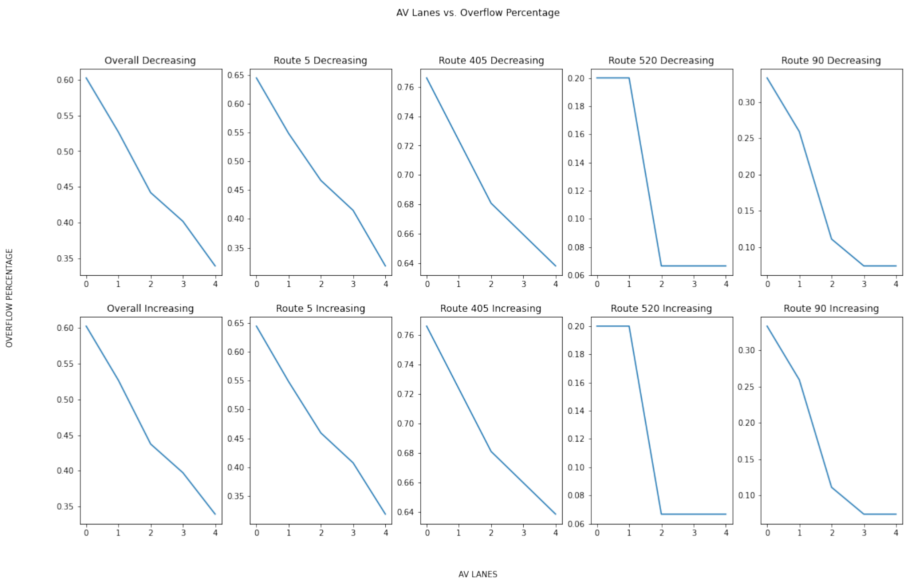

Figure 7: Autonomous Vehicle Lanes Impact on Overflow Percentage

Figure 8 shows autonomous vehicle lane inclusion versus overflow percentage. This showed a linear relationship for routes 405, 5, and 90 as well as the overall results. Route 520 saw a steep decline with the inclusion of two autonomous lanes. Overall, both measures showed similar results to those of the autonomous vehicle penetration

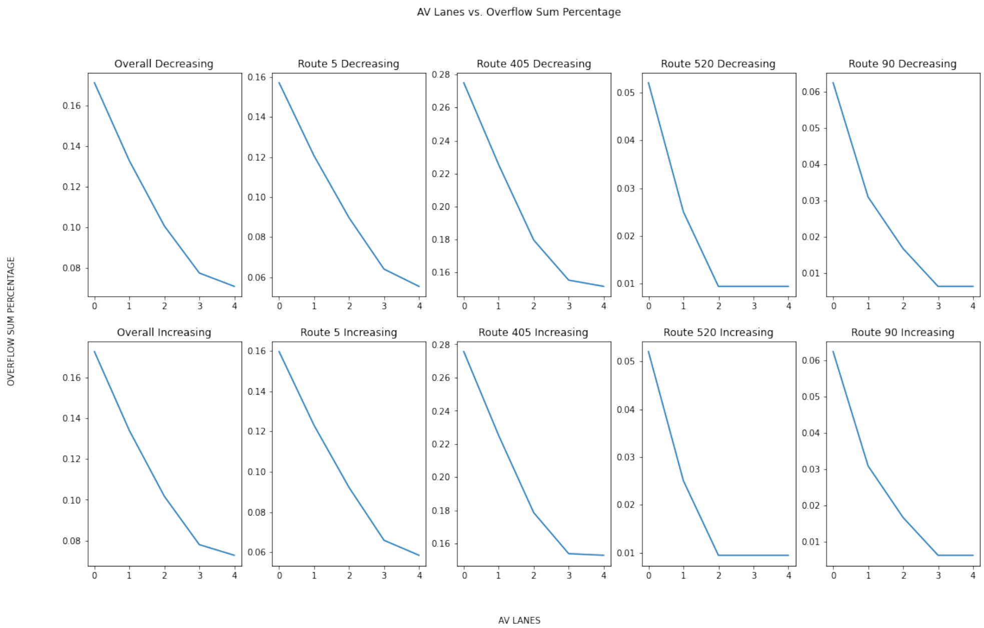

Figure 8: Autonomous Vehicle Lanes Impact on Sum Overflow as a Percentage of Total Traffic

Steps were taken in order to compare the results of both the percentage and lane approaches. A method was required to compare lanes (a numeric value) to penetration percentages (a percentage). For each number of lanes, the percentage of total traffic for each highway that flowed through that number of lanes was calculated.

Lanes	Traffic Percentage INCR milepost	Traffic Percentage DECR milepost
1	0.317557	0.317557
2	0.635114	0.635115
3	0.900916	0.892740
4	0.983987	0.986690

Figure 9: Traffic Percentages of Lanes

A comparison between autonomous vehicle penetration and autonomous traffic lanes based on overflow percentage is shown in Figure 10. The overflow percentages for most of the lane data lined up with where they would be expected to fall based on the traffic percentages of those lanes. This suggests minimal impact in segregating traffic based on autonomy.

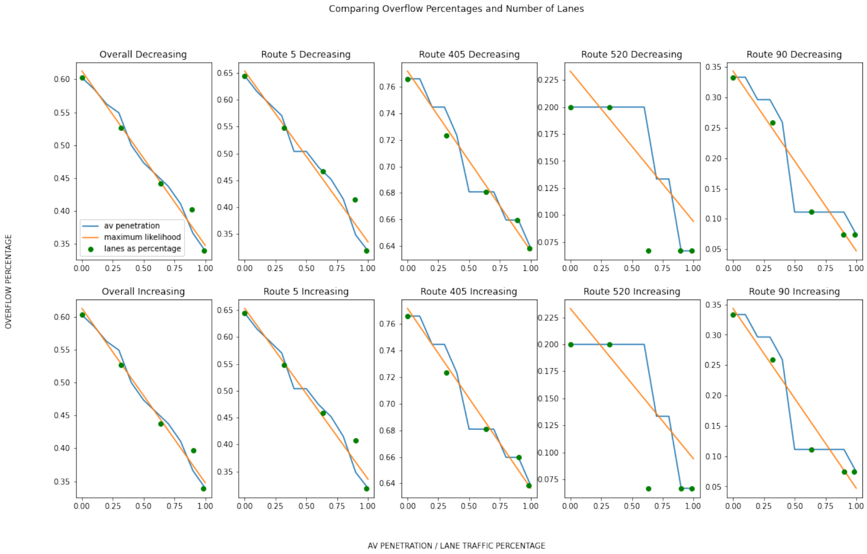

Figure 10: Comparing the Impact of Autonomous Vehicle Lanes and Penetration by Overflow Percentage

Figure 11 shows a similar comparison to Figure 10 now based on overflow sum percentages. The results were mostly the same, however it appears the lane approach outperformed straight AV penetration on both Route 405 and Route 520. This suggests that segregating traffic on these roads might be a place to look in further research.

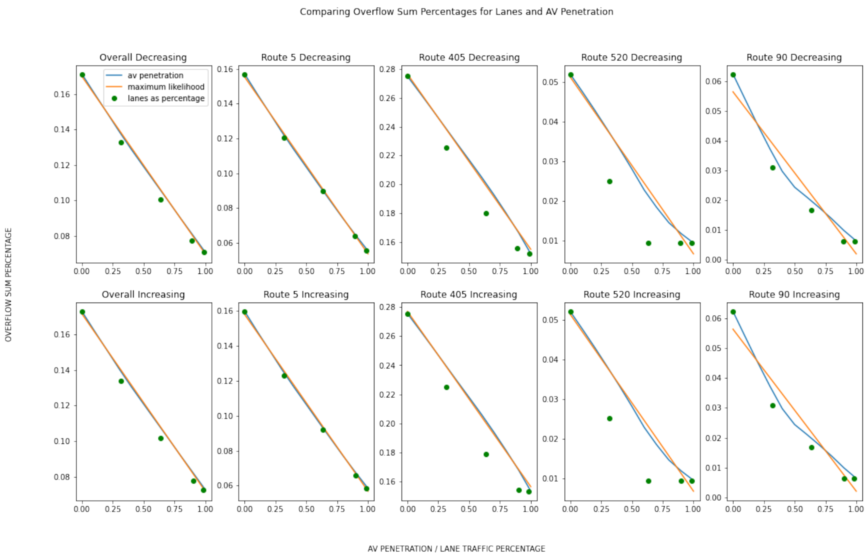

Figure 11: Comparing the Impact of Autonomous Vehicle Lanes and Penetration by Overflow Sum Percentage

Analysis

Based on the models used in this study, autonomous vehicle penetration appears to have a linear relationship with traffic overflow. This result suggests that while autonomous vehicles will improve the flow of the traffic system, there is no evidence to suggest that increasing percentages of autonomous vehicles will produce better results with traffic segregation. Human-driven cars in this matter do not seem to disrupt the flow of the autonomous vehicles. While it might be expected that as less human drivers are on the road, the communication between these vehicles might create better and better results, our models suggest this is not the case. This result suggests that segregating traffic by driver would not have any better of an impact than just allowing the self-driving cars to intermix with human drivers.

The results of this study could be as much a result of the models used as the data analyzed. Traffic flow is a complex study of mathematics that requires equally complex models to diagnose. The utilization of advanced models was not possible given the time constraints of the project. More advanced models could provide better insight into the potential benefits of autonomous vehicles and the segregation of autonomous traffic. More tangible results could have been derived from advanced models.

Further research could be done into the impact of autonomous vehicles based on the amount of traffic in a system. Different highways showed different results in some of the models. A possibility of these discrepancies could be that different highways, or sections of highway, have differing levels of traffic, and it is possible that autonomous vehicles have a different impact based on the amount of lanes/traffic.

Summary

At the very least, this study suggests that greater research should be done into the impact of autonomous vehicles on the Puget Sound area. Autonomous vehicles could provide a significant positive impact on the traffic flow of this area. Traffic overflow can be cut down markedly on some major routes with the inclusion of autonomous vehicles. In the study, Overflow percentage overall was cut down from 60.2 percent of highway sections to 50 percent with 40 percent autonomous vehicle penetration. The results of this study suggest that increasing autonomous vehicle penetration in any capacity would be good for the Puget Sound area.

Source Code on Github

Jupyter notebooks for this project as well as data and sources can be found at the link below:

`https://github.com/tliggett/sound_traffic`

References

[1] Ratrout, Nedal T., and Syed Masiur Rahman. "A COMPARATIVE ANALYSIS OF CURRENTLY USED MICROSCOPIC AND MACROSCOPIC TRAFFIC SIMULATION SOFTWARE." *A COMPARATIVE ANALYSIS OF CURRENTLY USED MICROSCOPIC AND MACROSCOPIC TRAFFIC SIMULATION SOFTWARE*, vol. 34, no. 1B, Apr. 2009, pp. 121–133., www.researchgate.net/profile/Nedal_Ratrout/publication/228676772_A_comparative_analysis_of_currently_used_microscopic_and_macroscopic_traffic_simulation_software/links/56eab2a808ae95fa33c8407b/A-comparative-analysis-of-currently-used-microscopic-and-macroscopic-traffic-simulation-software.pdf.

[2] "Traffic Data Computation Method." *U.S. Department of Transportation*, Federal Highway Administration, Office of Highway Policy Information, Aug. 2018, www.fhwa.dot.gov/policyinformation/.

[3] Lu, Qiong, et al. "The Impact of Autonomous Vehicles on Urban Traffic Network Capacity: an Experimental Analysis by Microscopic Traffic Simulation." *Transportation Letters*, 6 Sept. 2019, pp. 1–10., doi:10.1080/19427867.2019.1662561.