Increased Capacity on Seattle Roadways

Control # 61916

January 23, 2017

Contents

1 Introduction

1.1 Background

Traffic flow in many cities is an obvious problem–traveling via highway is not as efficient as planned and this lack of efficiency can impede economic productivity. For example, a region that experiences heavy traffic flow is the Seattle area. Some of the roadways in this area that experience these heavy traffic flows include Interstates 5, 90, and 405, and along Route 520. An obvious solution is to increase the capacity of the highway by constructing more lanes, but this is time consuming, causes delays due to construction, and can be very costly. However, the introduction of self-driving cars may present an alternate solution to the problem and would not have many of the disadvantages that construction would have. A self-driving, cooperating vehicle does not have a driver; it is managed by computers, receives data from highly accurate sensors, and is able to communicate with other self-driving, cooperative vehicles. Self-driving, cooperative cars decrease the distance between cars since they are faster and more accurate when responding to changes in acceleration.[1]

1.2 Goals

- To model the effects of the addition of self-driving, cooperating cars in Seattle traffic.
- To model the effects of the addition of self-driving car and the addition of a lane dedicated to these cars.
- To compare the effects of each model on the traffic flow, and determine which model is most effective to improve traffic flow.

1.3 Data Provided

The data provided includes information on the roads in question and a map of the roadways and their counties. Data on each road includes start and end distance for each milepost, average daily traffic counts through each milepost from 2015, the number of lanes on each road segment in either direction, and any significant intersections along the road. This data will be used to calculate the average density of cars (in cars per mile) and the flow rate (in cars per hour) over each segment of road.

1.4 Assumptions

1.4.1 Regular Vehicles v. Self-Driving, Cooperating Vehicles

The length of a vehicle is considered to be the physical space that the car occupies and the distance that it leaves between it and the car immediately in front of it. For both self-driving and non-self-driving vehicles, the physical length of the cars is assumed to be 177.2 [3] inches. However, the space allotted in front of each vehicle differs. For a regular vehicle, the minimum distance that a car leaves between it and the car in front of it is described by the "three-second rule" during free-flow traffic. This means that for traffic going a maximum of 60 miles per hour, the distance in front of each regular car is 3168 inches. For a self-driving vehicle, the minimum distance in front of it depends on the type of vehicle it is following. If the car in front of a self-driving vehicle is a regular car, then the minimum space allotted in front of the self-driving vehicle is also described by the "three-second rule". The space that a self-driving vehicle leaves between itself and another self-driving vehicle is assumed to be 177.2 inches at 60 miles per hour[1].

1.4.2 Traffic Density and Traffic Flow

The models that were developed only consider traffic in free-flow which is significant because during heavy traffic, the actual capacity exceeds the maximum free-flow capacity. Traffic density will be modeled based on the space that each vehicle on the road occupies. Both the average traffic density and the maximum traffic density during free-flowing traffic periods must be calculated. The average density of the vehicles over a segment of road is determined using the data provided and assuming that the average traffic density will not change with the addition of self-driving vehicles to the roadways. The maximum density along a segment of road is determined by its length, the average length that each car is expected to occupy, and the number of lanes on that road segment. With the addition of self driving cars, the maximum density of each road segment is expected to increase.

1.4.3 50/50 Traffic In the Negative and Positive Directions

It will be assumed that 50% of the vehicles on the road at any given time will be going in the positive direction (i.e. Northbound or Eastbound), and the other 50% of the vehicles on the road will be going in the negative direction (i.e. Southbound or Westbound).

1.5 Modeling Outline

1.5.1 Model 1: Integrating Self-Driving Vehicles Onto the Roadways

The first model will calculate the overall velocity that the vehicles will be going along each roadway based on the average and maximum densities of the roads. In this model, it is assumed that the maximum speed that any vehicle will reach is 60 miles per hour. The velocities of the vehicles on each road segment will be calculated when 0%, 10%, 50%, and 90% of the vehicles on the roads are self-driving vehicles.

1.5.2 Model 2: A Designated Lane for Self-Driving Cooperating Vehicles

The second model will allocate a lane for self-driving vehicles along each of the roadways. The maximum velocity of all lanes is assumed to be 60 miles per hour and the expected velocities of the vehicles on each road segment will be calculated when there are 0%, 10%, 50%, and 90% self-driving vehicles.

1.6 Thesis

- The addition of self-driving vehicles during free-flowing traffic would improve the overall traffic flow significantly.
- The addition of the designated lanes for self-driving vehicles will also improve overall traffic flow significantly for roads with three or greater lanes when there are more than 10% of self-driving vehicles occupying the roads.

2 Model 1: Integrating Self-Driving Vehicles Onto the Roadways

2.1 Introduction

As stated before, this model of free-flowing traffic will determine the velocity along each road segment. This model will also include the change in velocity along each roadway with a 10%, 50%, and 90% increase in self-driving vehicles. For simplicity, it will be assumed that all vehicles will be evenly distributed amongst the lanes.

2.1.1 The LWR Model

The LWR Model is a well-known and celebrated model that treats free-flowing traffic as a fluid. The initial part of the LWR model will be used to calculate the overall velocity along a roadway given the road's speed limit (v_{max}), the maximum density of the road (ρ_{max}), and the density of the road at a given time (ρ). [2]

The average density of the vehicles on the roadways is calculated using the data provided and is assumed to not change when more self-driving vehicles are added to the roads. Thus it can be assumed that the density will remain unchanged. The average density along each road segment is estimated using the average daily traffic flow (in cars per hour), q, and the speed limit:

$$\rho_{average} = \frac{q}{v_{max}}$$

The maximum capacity of the roads during free-flowing traffic will change with the addition of self-driving vehicles since the distance between two self-driving vehicles is less than the distance between any two other vehicles. The maximum density along a road segment will be calculated geometrically using the maximum number of vehicles (c_{max}), the number of lanes (n), the length of the road (L), and the average length of the vehicles on the road ($l_{average}$):

$$\rho_{maximum} = \frac{c_{max} \cdot n}{L} = \frac{n}{l_{average}}$$

The average length of a vehicle will be calculated using the probability that there are two self-driving vehicles next to each other. Therefore the estimated velocity along a road segment can be represented with an equation that takes the speed limit, the traffic flow, the average length of the cars on the road, and the number of lanes on each road segment as input. With the addition of self-driving vehicles, the only variable that changes is the average length of the vehicles.

$$v = v_{max}(1 - (\frac{q \cdot l_{average}}{v_{max} \cdot n})^2)$$

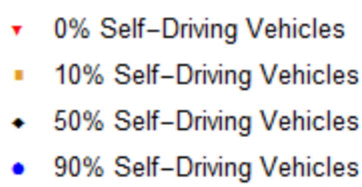
2.2 Results

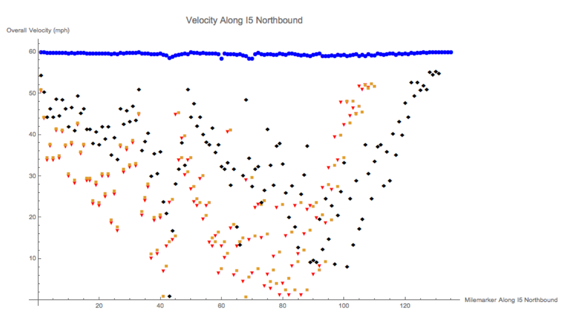
The maximum capacity of the road segments were calculated for free-flowing traffic, however in cases for heavy traffic, the actual capacity of vehicles exceeds this maximum capacity and, as a result, negative velocities are generated by the model. These negative velocities are most likely describing congested traffic and will be taken out of model since they do not describe free-flow traffic. With the integration of self-driving vehicles on the roadways, the overall velocity of the road segments increases and approaches the speed limit. The change in velocity over each roadway is shown in the table below:

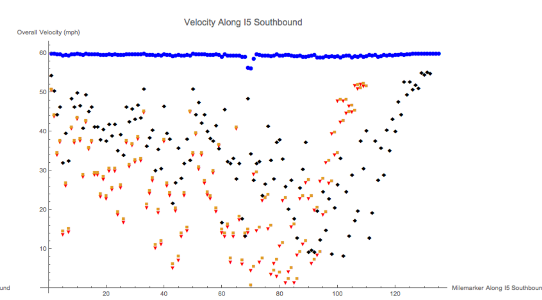
Road Name	Percent Increase of Self-Driving Vehicles	Velocity Increase (miles per hour)
I-5	0%-10%	0.267
	0%-50%	9.54
	0%-90%	33.9
I-90	0%-10%	0.404
	0%-50%	9.01
	0%-90%	22.4
I-405	0%-10%	-0.503
	0%-50%	4.33
	0%-90%	32.6
State Route 520	0%-10%	0.301
	0%-50%	6.82
	0%-90%	18.4

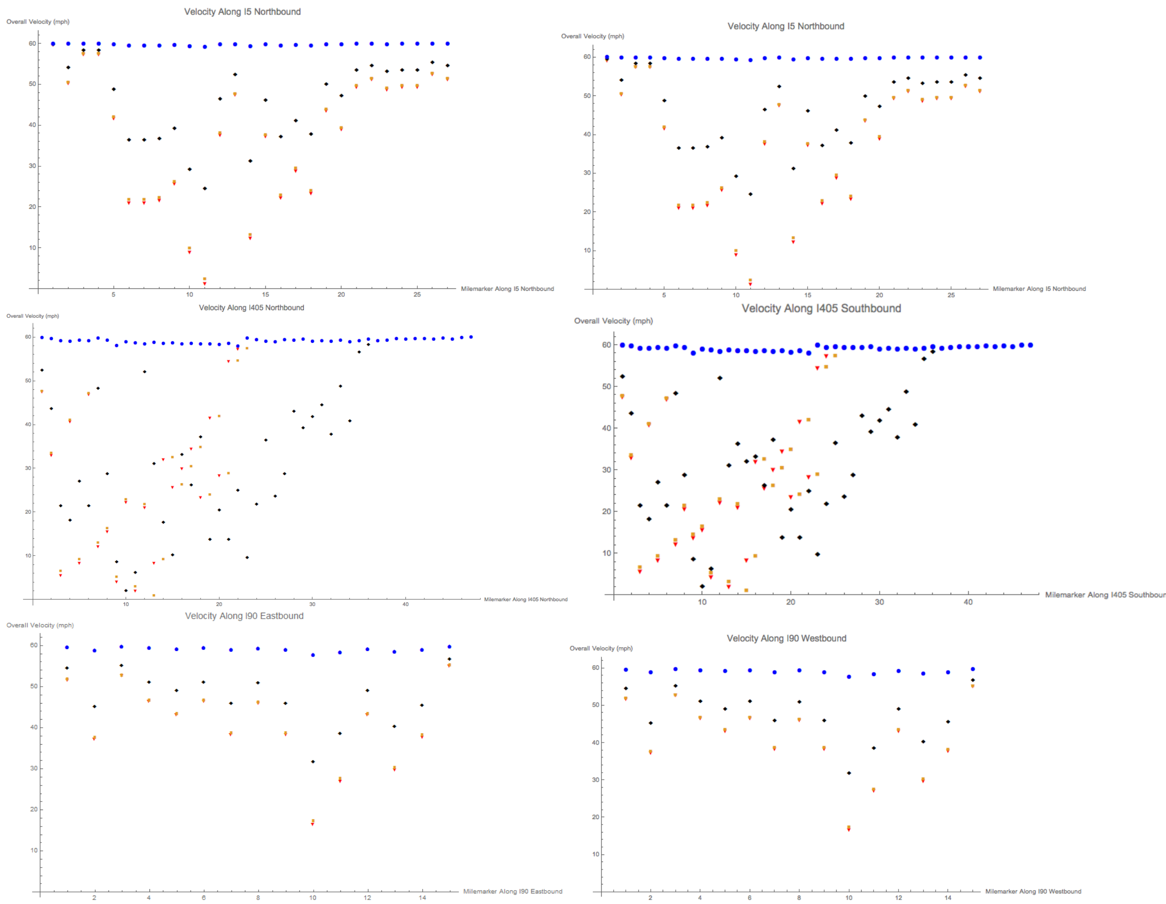
The average increases in velocity with the addition of 10%, 50%, and 90% self-driving, cooperating vehicles are 0.117 miles per hour, 7.42 miles per hour, and 26.9 miles per hour respectively.

The following graphs show the average velocities along each road segment at 0%, 10%, 50%, and 90% self-driving vehicles.









As shown, the addition of 10% self-driving vehicles does not create a substantial increase in traffic flow. However, larger percentages such as 50% and 90% self-driving vehicles shows a remarkable increase in overall velocity along these roadways. The addition of self-driving, cooperating cars does significantly increase the maximum capacity of the roads during free-flowing traffic and will increase the average velocity of these roadways.

3 Model 2: A Designated Lane for Self-Driving Cooperating Vehicles

3.1 Introduction

Since the addition of self-driving vehicles on the roadways increases the overall velocity, the addition of a lane specifically dedicated to self-driving vehicles may also increase the overall velocity of each roadway. In this model, a lane will not be added to each road segment, but one of the existing lanes will be dedicated to self-driving vehicles. For simplicity, it will be assumed that 100% of self driving vehicles will be located in their dedicated lane and 100% of non-self-driving vehicles will be located in the remaining, available lanes. Also, it will be assumed that all non-self-driving vehicles will be divided evenly amongst the lanes they are located in. This means that the maximum density is expected to increase even further with the addition of self-driving vehicles since 100% of self-driving vehicles will be behind other self-driving vehicles and they will be able to take advantage of the shorter distance between two self-driving cars. This model will find the velocity along each segment of road using the equation from the first model:

$$v = v_{max}(1 - (\frac{q \cdot l_{average}}{v_{max} \cdot n})^2)$$

The maximum velocity is assumed to be 60 miles per hour in all lanes. This model will describe the average velocity of the roadways at 0%, 10%, 50%, and 90% self-driving vehicles. It will also look at the average change in velocity as the percent of self-driving cars changes and the number of lanes changes.

3.2 Results

The average velocity of these roadways where every road segment has a lane dedicated to self-driving vehicles is as follows:

Road Name	Percent Increase of Self-Driving Vehicles	Velocity Increase (miles per hour)
I-5	0%-10% 0%-50% 0%-90%	1.13 9.07 29.9
I-90	0%-10% 0%-50% 0%-90%	-2.17 9.90 15.3
I-405	0%-10% 0%-50% 0%-90%	-0.0207 6.53 31.1
State Route 520	0%-10% 0%-50% 0%-90%	-7.40 13.0 25.3

When there are 10% of self-driving vehicles on the road and they are given their own lane, the average velocity decreases by 2.66 miles per hour. Where there are 50% and 90% self-driving vehicles on the road with their own lanes, the average velocity increases by 9.62 miles per hour and 25.5 miles per hour. In general, the addition of a lane dedicated to self-driving vehicles will impede traffic flow if there are only 10% self-driving vehicles on the roads. The addition of a lane dedicated to self-driving vehicles on a roadway will only significantly improve traffic when there are about 50% self-driving vehicles or more. However, the dedication of a lane for self-driving vehicles will have different effects on roads with different numbers of lanes. The change in average velocity for each number of lanes along all roadways of interest is shown in the following table:

Number of Lanes Along the Roadways	Change in Velocity (mph) with 10% Self-Driving Vehicles	Change in Velocity (mph) with 50% Self-Driving Vehicles	Change in Velocity (mph) with 90% Self-Driving Vehicles
2 Lanes	-5.07	-15.5	12.3
3 Lanes	-0.0961	15.6	28.8
4 Lanes	-2.09	19.5	28.6
5 Lanes	-0.370	19.5	27.5

As explained before, a lane dedicated to self-driving vehicles will not improve the traffic flow along these roadways if there are only 10% self-driving vehicles occupying the roads. In general, for a road with 3 or more lanes and with an occupancy of self-driving vehicles greater than 10%, a road dedicated to self-driving vehicles would improve traffic flow.

Since the roadways have a different number of lanes on each of the segments, the dedication of a lane for self-driving vehicles on the roads will have a different effect to the overall velocity depending on the number of lanes in that segment. In the following diagrams, the overall velocities of each roadway, calculated at 10%, 50%, and 90% self-driving vehicles, is shown at two, three, four, and five lanes. This data is then compared to the modeled velocity of roadways with 0% self-driving vehicles without a lane dedicated to self-driving vehicles (the data from Model 1).

Figure 1: I-5 Northbound and Southbound

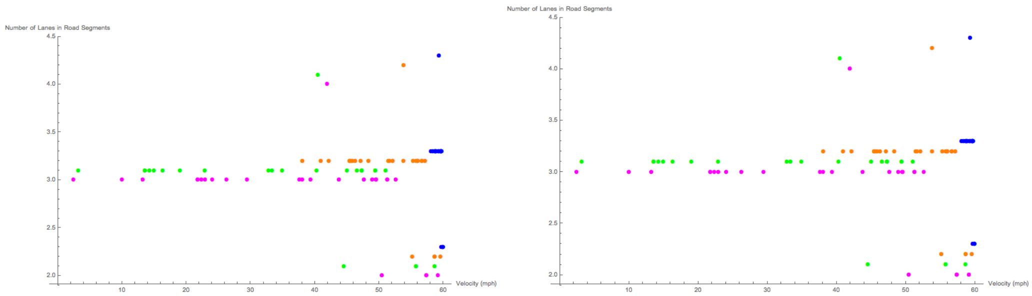


Figure 2: I-90 Eastbound and Westbound

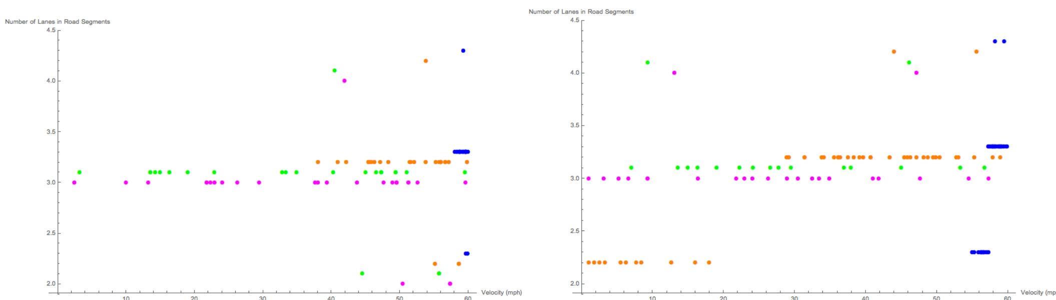


Figure 3: I-405 Northbound and Southbound

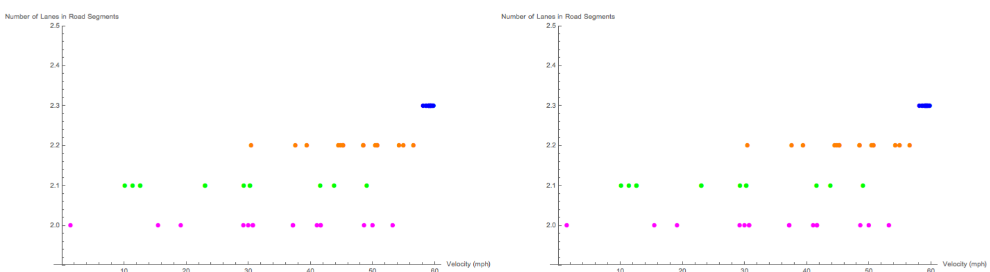


Figure 4: State Route 520 Eastbound and Westbound

These visual representations show us that for larger percentages of self-driving vehicles and for roadways with three or more lanes, there is a much larger increase in velocity when a lane is dedicated to self-driving vehicles.

4 Conclusion

4.1 Model 1 v. Model 2

Generally, Model 1 shows some increase in velocity no matter how many self-driving cars were added, but Model 2 only shows an increase when the percentage of self-driving cars exceeded 10% and the number of lanes exceeded two. Model 1 shows an increase for any amount of self-driving cars because no matter how many self-driving cars are added, the maximum density would increase, resulting in an increase in velocity. This means that if a larger percentage of self-driving cars are on the roadway, then there will be an improvement in traffic flow. However, Model 1 shows that the improvement with only 10% self-driving cars is so small that it is negligible. In fact, it has a slight adverse effect on the I-405. The effect is noticeable when the amount of self-driving cars reaches 50%, because, by this point, the difference in velocity reaches about 10 miles an hour. Model 2, as opposed to Model 1, gives the self-driving cars their own lane. This model shows a decrease in velocity for both small percentages of self-driving cars and when the self-driving cars were allotted one lane on a two lane road. For any number of lanes, it was slightly worse to give the self-driving cars their own lane when only 10% of all cars were self-driving. By the time the number of self-driving cars had increased to 50%, however, there was a marked improvement in the speeds of the vehicles. The results from the model for 90% self-driving cars in two lanes where one lane was dedicated to self-driving cars was unexpected; even though 90% of cars are in one lane, the improvement in the overall density caused by self-driving cars is so great that the velocity was improved.

4.2 Overall Conclusion

The problem for heavy traffic in the Seattle area can be solved with the addition of self-driving vehicles along highways because they would increase the maximum capacities of the roads and increase the efficiency of traffic. First, a geometric model was used to determine the maximum capacity of the roadways. Then, the data provided was used to estimate the average density along each road. These two values were then used in the modified LWR Model to quickly determine the effects of integrating self-driving, cooperating vehicles into the Seattle area roadways. With this model, it can be seen that self-driving vehicles really do improve traffic flow, especially at large percentages of self-driving vehicles on the roads. Namely, the benefits of self-driving vehicles are experienced when there is a high percentage of self driving vehicles. Also, dedicated lanes for self-driving vehicles should only be introduced to roads with three or more lanes after the percentage of self-driving vehicles exceeds 10%. Self-driving, cooperating vehicles are an effective way to increase the capacity of the roadways and to improve traffic flow.

References

[1] *Autonomous intelligent cruise control - IEEE Xplore Document.* URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=260745.

[2] Mh Kabir, Mo Gani, and Ls Andallah. "Numerical Simulation of a Mathematical Traffic Flow Model Based on a Nonlinear Velocity-Density Function". In: *Journal of Bangladesh Academy of Sciences* 34.1 (2010). DOI: 10.3329/jbas.v34i1.5488.

[3] *What is the average length of a car?* URL: https://www.reference.com/vehicles/average-length-car-2e853812726d079d.