For office use only	Team Control Number	For office use only
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T3 ________________	Problem Chosen	F3 ________________
T4 ________________	C	F4 ________________

2017
MCM/ICM
Summary Sheet

(Your team's summary should be included as the first page of your electronic submission.)
Type a summary of your results on this page. Do not include the name of your school, advisor, or team members on this page.

As self-driving vehicles becomes a fast-growing and highly focused field, they will soon be part of our daily life. This paper analytically references and extend existing models on the following relations:

- **Highway capacity, safe distance and vehicle types**, where vehicle types include manual vehicle, self-driving car with sensor, self-driving car with sensor and vehicle-to-vehicle (v-to-v) communication, manual vehicle with sensor and v-to-v communication

- **Highway traffic flow and density**. LWR Models with Triangular Fundamental Diagram is selected for its empirical accuracy, and simplicity to integrate the previous model

These two model are integrated by generating density from the former model, which serves as parameter for the later. The overall model establishes a relation between highway theoretical max flow per lane and proportion of self-driving car.

Given data is analyzed and processed to fit format of our model. Specifically, we use online data source to statistically obtain the length of peak hour, and convert AADT into traffic flow per lane per hour. By comparing this value to theoretical max flow per lane from model, we found many segments of I-9, I-90, I-405 and SR-520 are overloaded with traffic. Actions need to be taken to resolve meet high traffic demand.

As one of the most easy-to-implement measures, dedicated lane policy is carefully analyzed. Based on established model, we derived specific formula for traffic flow with and without dedicated lane. Then thresholds of self-driving car proportion necessary to make dedicated lane policy efficient is calculated. For example, 2-lane highway requires at least 58% percent of self-driving car, or can worsen the current traffic; 4-lane highway, however, could benefit from dedicated self-driving car lane with only around 28% of self-driving cars.

Due to limited time, we make quite a few assumptions to make our model simple but is still able to capture the essential ideas, and still able to provide insights. Specifically, vehicles are abstracted to types as mentioned in first model, which ignores any individual differences. As deterministic model, it performs poorly on capturing variability. Stochastic models can be great direction for further research as time allows.

1 Statement and Clarification of Problem

Self-driving car is identified as one of means to increase highway capacity. This paper analyze the effect of self-driving car to highway capacity, and traffic flow in peak or average hours. Two models are proposed base on previous research and analysis to capture relation between:

- highway capacity (yielding jam density with simple computation) and percentage of different types of cars on highway, where types of cars includes:
  - manual cars
  - self-driving cars with sensor
  - self-driving cars with sensor and vehicle-to-vehicle communication
  - manual cars with sensor and vehicle-to-vehicle communication
- traffic volume per unit time and density of traffic, with jam density as parameter (which can be obtained from the previous model).

Based on proposed models, we then calculated expected improvements for Interstates 5, 90, and 405, as well as State Route 520 are generated using their annual traffic data from year of 2015.

Additionally, as part of self-driving car and non-self driving car interaction, we carefully analyze dedicated lane policy for self-driving car with respect to different self-driving car proportions. Key proportions that justifies dedicated lane policy are also provided. For cooperation between self-driving car, we referenced existing paper of vehicle to vehicle communication system. Model is also extended to include communication between self-driving vehicle and non-self-driving vehicles.

2 Assumptions and Rationale/Justification

Assumptions:

- Self-driving car are perfectly designed to obey the traffic laws, and can only be at fault if malfunctioning.
- There are only four types of vehicle possible on road. They are:
  - manual cars
  - self-driving cars with sensor
  - self-driving cars with sensor and vehicle-to-vehicle communication
  - manual cars with sensor and vehicle-to-vehicle communication
- For simplicity, same type of vehicle share the same response time to emergency situation, and all vehicle shares the same maximum deceleration rate, vehicle length etc.
- All vehicle on the same lane are traveling at the same speed. This assumption simplify the problem quite a lot while it does not bias models much:
  - Individuals who drive with abnormal speed are ignored, and traffic speed (or average speed) is taken.
  - Overtaking is implicitly considered. At low density,

Variables:

- v, speed of traffic. Unit usually takes ($mile * hour^{-1}$).
- ρ, density of traffic defined as number of vehicles per unit of length on one lane. Unit usually takes ($mile^{-1}$).
- ρ_j, jam density, or average maximum density when vehicles are in perfect jam. Sometime this is also referred to as ρ_{max}
- ρ_c, density threshold value, which free flow happens if and only if density is no greater than this value.
- f, flow of traffic defined as number of vehicles passing a given point per unit of time. Unit usually takes ($hour^{-1}$)
- f_{max}, maximum flow, which only happens at optimum density.

- v_f, free flow speed.
- l, length of vehicle.
- d, expected safe distance for a mixture of vehicles.
- t, expected reaction time for a mixture of vehicles.

3 Model Design and Justification

3.1 Single Lane Safe Distance Model based on Vehicle Types

This model is an extension of model by Tientrakool, Ho, & Maxemchuk (2011). Our model in addition consider manual vehicle with sensor and communication devices, where these devices are supposed to provide more obvious warning in visual, sound or some other form that substantially decrease driver's response time to emergency stop of previous vehicles. Similar devices are already in use for many cars. We expect drivers on general are therefore more comfortable and capable of maintaining shorter following distance and lower accident rate.

With some further simplification using our assumption such as common max decelerations, most import results from Tientrakool et al., 2011 is paraphrased here:

- Suppose highway consists of each type of vehicle with proportion below:

Vehicle Type	Proportion
Manual	p_m
Self-driving w/ Sensor	p_s
Self-driving w/ Sensor and Communication	p_c

Since communication devices are useful only if the proceeding vehicle is also equipped with communication device, types of proceeding vehicles result determine safe distances. Let d_m denotes safe distance of manual vehicle, d_s that of self-driving vehicle with sensor or self-driving vehicle with sensor and disabled communication, d_c self-driving vehicle with enabled communication respectively. Assuming random distribution of vehicle types, the proceeding vehicle is or is not communicative with probability p_c and $1 - p_c$ respectively. With this assumption, the following table is obtained:

Vehicle Type	Safe Distance	Probability
Manual	d_m	p_m
Self-driving w/ Sensor	d_s	p_s
Self-driving w/ Sensor & Cmn following non-cmn	d_s	$p_c \cdot (1 - p_c)$
Self-driving w/ Sensor & Cmn following cmn	d_c	p_c^2

With communication devices to being available in recent years, we may consider another type of "vehicle": manually driven car with assists of sensor and communicative device. This type of car has clear advantage comparing to both traditional manual vehicle and self-driving ones because driver can be warned for emergency earlier thus allowed more time to react, but it is also cheaper than a fully self-driving car. Research shows that reaction time of normal driver is around 1.1 sec, whereas human can react to sound or touch in around 0.2 sec on average (Brains, 2009) . When the proceeding vehicle approaches, human driver takes more time to determine if a emergency stop is necessary. However, with help of sensor and communication devise, a shorter safe distance can be obtained. Note that comparing to response time of human, response time difference between sensor and v-v communication is negligible. For simplicity, we do not distinguish the type of proceeding vehicle. Let proportion of manual car be p_{mc}, and safe distance be d_{mc}, the cases can be updated:

Vehicle Type	Safe Distance	Probability
Manual	d_m	p_m
Self-driving w/ Sensor	d_s	p_s
Self-driving w/ Sensor & Cmn following non-cmn	d_s	$p_c \cdot (1 - p_c - p_{mc})$
Self-driving w/ Sensor & Cmn following cmn	d_c	$p_c \cdot (p_c + p_{mc})$
Manual w/ Sensor & Cmn	d_{mc}	p_{mc}

Safe distance can be calculated using

$$d_{case} = t_{case} * v$$

To obtain an average safe distance, we use its expected value:

$$\begin{aligned} d &= \textstyle\sum_{case} d_{case} * p_{case} \\ &= v \cdot t_m \cdot p_m + v \cdot t_s \cdot p_s + v \cdot t_{mc} \cdot p_{mc} \\ &\quad + v \cdot t_s \cdot (p_c \cdot (1 - p_c - p_{mc})) + v \cdot t_c \cdot (p_c \cdot (p_c + p_{mc})) \end{aligned}$$

where speed v and proportion p_m, p_s, p_c, $p_m c$ are given based on highway statistics, and response time will be given in "model result" section as constants. For convenience of later model, we may also estimate expected gap time as expected response time:

$$t = \frac{d}{v}$$

3.2 Flow Model based on Density

Flow is defined to be the product of speed and density.

$$f = v \cdot \rho$$

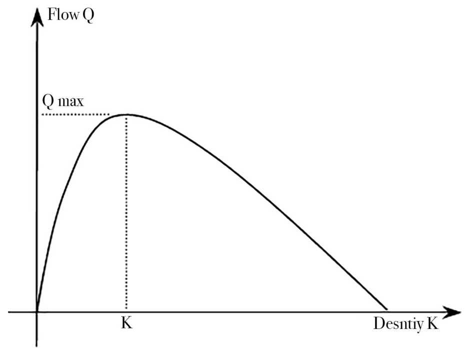

Figure 1: Greenshield's flow-density model

Although we generally know that flow first increases along with density until obtaining some maximum flow, and decreases as density further increases and approach jam density, the exact relation is not trivial. Fundamental diagram of traffic flow is the diagram that captures the relation. There are already many existing model proposed by previous researchers. Here we present a few of them and pick one based on empirical results.

- **Greenshield's Model (First Fundamental Diagram)**
  Greenshield's model was originally derived from the observations by Greenshield about 84 years ago in 1933. The model is under the assumption that under the condition without interruption, the relationship between vehicles' velocity and density is linear. Even though the model is fairly accurate, its simplicity makes it one of the most popular models to be used when exploring the relationships between speed and density.

  Greenshield's model propose a relation between speed and density:

  $$v = (1 - \frac{\rho}{\rho_{max}} v_f)$$

  To obtain a relation between flow and density instead, we multiply both sides by density ρ:

  $$f = (\rho - \frac{\rho^2}{\rho_{max}} v_f)$$

- **LWR Models with Triangular Fundamental Diagram**

  $$f = \begin{cases} v_f \cdot \rho & \text{if } \rho \leq \rho_c = \frac{1}{v_f \cdot t + l + d} \\ \frac{1}{t} \cdot (1 - \frac{\rho}{\rho_{max}}) & \text{otherwise} \end{cases} \tag{1}$$

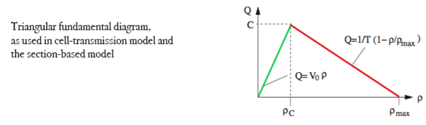

Figure 2: LWR Models with Triangular Fundamental Diagram (Treiber & Kesting (2013))

By empirical results and the fact that the LWR triangular models emerged later than the original Greenshield's model, the LWR model tends to be more accurate. Additionally it simplify our process of calculating max flow allowed by highway, which would be used a lot in later sections (Hole, 2008).

4 Model Results with Application to Interested Highways

4.1 Model Results

From Tientrakool et al., 2011 section VI, we found reaction time for all its proposed vehicle types. It is generally believed that human has on average reaction time less than 0.2 to sound and touch stimuli, but given that most driving do not dare to risk following proceeding car closely even with the devise, we assign value 0.7. This value can be very inaccurate but there do not seem to be available data for this found publicly.

Vehicle Type	Reaction Time (From emergency to brake applied)
t_m : Manual	$1.1 + 0.1 = 1.2$
t_s : Self-driving w/ Sensor	$0.245 + 0.081 = 0.326$
t_c : Self-driving w/ Cmn.	$0.181 + 0.081 = 0.262$
t_{mc} :Manual w/ Cmn	$0.7 + 0.1 = 0.8$

Additionally for all vehicles: length is set to be $4.3m$, free flow speed $v_f = 60mile/hour$ The worst case is when all vehicle are manually driven without any sensors nor communication devices. Using models proposed, we obtain the followings:

- At v_f, average safe distance $d = v_f \cdot t_m = 60 \cdot 0.44704 \cdot 1.2 = 32.19m$
- $\rho_c = \frac{1}{v_f \cdot t + l + d} = \frac{1}{32.19 \cdot 2 + 4.3} = \frac{1}{68.68} m^{-1}$
- The max traffic flow $f_m ax = v_f \cdot \rho_c = \frac{60 \cdot 0.44704}{68.68} = 0.39 s^{-1} = 1405 h^{-1}$, 1405 vehicles per hour per lane.

The best case is when all vehicle are self-driving car with vehicle to vehicle communication. Using models proposed, we obtain the followings:

- At v_f, average safe distance $d = v_f \cdot t_c = 60 \cdot 0.44704 \cdot 0.262 = 7.02m$
- $\rho_c = \frac{1}{v_f \cdot t + l + d} = \frac{1}{7.02 \cdot 2 + 4.3} = \frac{1}{18.34} m^{-1}$
- The max traffic flow $f_m ax = v_f \cdot \rho_c = \frac{60 \cdot 0.44704}{18.34} = 1.46 s^{-1} = 5256 h^{-1}$, 5256 vehicles per hour per lane. Ideally a single lane nearly matches sum of of all lanes peak hour traffic flow on I-5 of WA.

Suppose 10%, 50%, 90% of vehicles are self-driving car, we plot relation between maximum flow and percentage of manual vehicle with communication devices below.

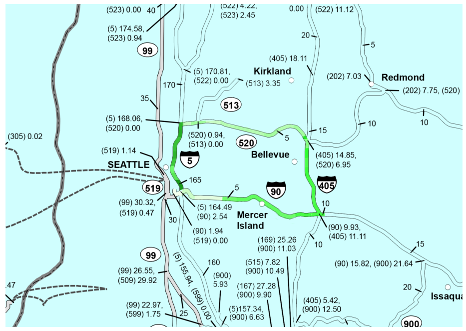

Figure 3: Traffic Density of Route I-5,I-90,I-405 and SR-520

4.2 Analysis of Given Dataset

The first step of our analysis is to convert AADT (Annual average daily traffic) which was provided in the given dataset to VMT (Vehicle Miles Traveled). Since AADT are rates and can not be manipulated, we convert them to VMT so that we can sum up to get the indicator that represents the amount of traffic a specific route has.

Since the VMT index has been used to decide federal findings for governors, we assume the index can also be applied to test the validity of our models as well as to provide ideas on how to make policies based on different routes.

The formula for the conversion from AADT to VMT is listed below:

$$\text{VMT} = \text{Length}_{\text{route segment}} \times \text{AADT}$$

Route ID	I-5	I-90	I-405	SR-520
VMT	17645710	2367950	4390900	967180

We also visualized the traffic density of the roads of interest by the map in the figure 3. The darker the colour is, the more dense the traffic flow is in that highway segment.

4.3 Peak Hour Calculation

Since exact length of peak hour is not provided, we try to obtain peak hours from online dataset ("Intelligent Network Flow Optimization (INFLO)," 2015).

- **Data Source**
  The comma separated values dataset, Intelligent Network Flow Optimization

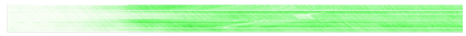

Figure 4: Visualization of traffic density

(INFLO) Prototype Small-Scale Demonstration from Seattle, WA, provides a detailed record for traffic volume of each minute for 110 routes in Washington.

- **Method**
  According to the background information stated in the problem, 8% of the daily traffic volume is the threshold for peak travel hours. Thus, we used a computer program to order the data by the volume of each minute. And select minutes until they sum up to 8% of the daily traffic volume. It is not hard to observe that during a specific period for each day, the selected minutes are concentrated and almost continuous. But, there still exists some samples showing that there are minor gaps between discrete time spots. So I tune this variable of grace period so as to cover about 8% of daily traffic during peak hours. And the grace period is 10 minutes on average. Moreover ,due to the incompleteness of data set, there are finally 55 valid routes such that they hold at least more than 30 records of valid data.

- **Result**
  The average peak length calculated from the program is 136 minutes, starting from 13:46 to 15:19. And a data visualization graph is shown below. Each square represents the volume of that route at that minute. And since this is a heat map of daily traffic volumes, the extent of green represents the traffic density. And from this graph, it is possible to visually validate the numerical results mentioned above.

Figure 4 is an visualization of dataset, where darker color corresponds to a higher density of traffic, horizontal axis represents time from low to high.

4.4 Model Application to Interested Highways

With model established, we may now consider expected improvements for Interstates 5, 90, and 405, and State Route 520. Lets assume currently all vehicles are non-self driving cars. We are given data on average daily traffic counts each highway segments and number of lanes, and are suggested that 8% of daily traffic occurs during peak travel hours. Peak travel hour on average is 1.5 hours long. Therefore, we obtain actual average flow per lane for peak hour traffic and average traffic using definition:

$$f_{actual} = \frac{\text{traffic count}}{\text{hour} \times \text{number of lane}}$$

Based on provided data, results are as following:

Route ID	I-5	I-90	I-405	SR-520
Max Daily Average Flow	2016.667	1125	1843.75	1135.417
Max Peak Flow	2581.333	1440	2360	1453.333

The above data clearly shows that current demand exceeds highway

4.5 Dedicated Lane Analysis and Decision Threshold

The advantage of dedicated lane is that it maximize benefit from the short safe-distance of self-driving car. Additionally, we may consider a higher speed limit for for self-driving cars since they ideally avoids all accidents, or at least better at handling emergency events. To maximize the capacity of highway, we try to maximize max flow of traffic. It is suggested that self-driving car are generally able to handle speed 10 miles beyond current speed limit. For the 4 routes we analyze, this mean an increased speed limit to 70 miles/hour rather than the original 60 miles/hour for self-driving car dedicated lanes.

We should consider the worst case when designing policies, that is, we assume all vehicle owners are not willing to equip vehicle to vehicle communication devices (possibly due to cost or incompatibility). If in reality quite a lot of people do install communication devices, results can only be better due to less safe distance required and also possibly less accidents.

At each percentage, we first compute their max flow with 60 mile/hour (26.8224 meter/sec) speed limit, then with 70 mile/hour (31.2928 meter/sec) speed limit for self driving car lanes. Computed average safe distance, free flow threshold density, and max flow per lane are listed below:

% self-driving	d_{avg} (m)	ρ_c (#/m)	f_{max} (#/hr)
0%	32.19	0.146	1406.08
10%	29.84	0.0156	1509.11
50%	20.47	0.0221	2134.83
90%	11.09	0.0378	3647.00
100%	8.74	0.0459	4431.79
100% with 70 mi/hr	10.20	0.0405	4560.36

Base on calculations above, we conclude that dedicated lane for self-driving car with increased speed-limit has most max single-lane traffic flow.

In order to determine the exact number of lanes that should be dedicated to self-driving car, we first consider a 2 lane road with self-driving vehicle only driven on dedicated lanes, with manual vehicle only on normal lane, both at max flow. Proportion of self-driving car in this case is

$$\text{self-driving porportion} = \frac{\text{dedicated lane flow}}{\text{total flow}} = \frac{4560.36}{4560.36 + 1406.08} = 0.76$$

meaning self-driving car would have to overflow to normal lanes if they take more than 76% of all vehicles. When below 76% we compare traffic flow with dedicated lane and non-dedicated lane with all levels of self-driving proportion, assuming dedicated lane can have less than maximum traffic flow due to not enough self-driving vehicle, while the normal lane always reaches max flow. Note that without dedicated lanes, each lane holds mixture of traffic flow rather than pure self-driving or manual vehicle flows. Let p denote percentage of self-driving car, then $c = \frac{f_{\text{self-driving}}}{f_{\text{manual}} + f_{\text{self-driving}}}$. Therefore traffic flow on dedicated lane is,

$$f_{\text{self-driving}} = \frac{p \cdot f_{\text{manual}}}{1-p}$$

Below we compute max total flow possible for the 2-lane route:

% self-driving	$f_{\text{no-dedicated}}$ (#/hr)	$f_{\text{with-1-dedicated}}$ (#/hr)	f_{diff}
0	2812.16	1406.08	-1406.08
0.1	3018.22	1573.76	-1444.46
0.2	3256.87	1813.19	-1443.68
0.3	3536.50	2163.90	-1372.60
0.4	3868.65	2695.63	-1173.02
0.5	4269.67	3540.91	-728.76
0.56	4552.83	4303.33	-249.50
0.57	4603.72	4457.38	-146.34
0.58	4655.75	4620.76	-34.99
0.59	4708.98	4794.25	85.27
0.6	4763.44	4978.66	215.22
0.7	5386.34	7690.15	2303.8

Observe that when self-driving car proportion is around 0.59, dedicated lane creates higher efficiency. Formally, we derive formulas from model for 2 lanes total flows in cases with and without dedicated lanes respectively,

$$f_{\text{max-no-dedicated}} = 2 \cdot \rho_c \cdot v = \frac{2v}{2t \cdot v + d}, \text{ where } t = t_m \cdot (1-p) + t_s \cdot p$$

$$f_{\text{max-dedicated}} = f_{manual} + \frac{p}{1-p} f_{manual}, \text{ where } f_m = 1406.08 \text{ from table above}$$

Setting them equal and solve for p, we obtain $p = 58\%$, which says one dedicated lane for 2-lane highway is useful if and only if we have self-driving car proportion higher than threshold of 58%.

Generally, when deciding if we need to add m_{th} dedicate lane when we already have an n-lane highways, we have the following:

$$\begin{aligned}
f_{\text{current}} &= (m-1) f_{\text{self-driving}} + (n-m+1) f_{\text{mix}} \\
f_{\text{mix}} &= \tfrac{v}{2v \cdot (q \cdot t_s + (1-q) \cdot t_m) + d} \\
p &= \tfrac{(m-1) f_{\text{self-driving}} + q \cdot (n-m+1) f_{\text{mix}}}{(m-1) f_{\text{self-driving}} + (n-m+1) f_{mix}} \\
f_{\text{add-dedicated}} &= f_{\text{manual}} \cdot (n-m) + \tfrac{p}{1-p} f_{\text{manual}} \cdot (n-m) \\
&= \tfrac{f_{\text{manual}}}{1-p}
\end{aligned}$$

where q = proportion of self-driving vehicle on non-dedicated lanes. By setting $f_{\text{current}} = f_{\text{add-dedicated}}$ and solving the system of above 4 equations for p, threshold proportion of self-driving car necessary to add m_{th} dedicated lane can be obtained.

5 Model Weakness Analysis

Our model is derived from analysis rather than regression on existing data, since there are no large enough existing data to rely on. Self-driving car is new technology, and naturally not much data is available to us. In this case, model testing is hard to accomplish - we have to wait and see how self-driving car perform as more of them gets on street.

Additionally, because of assumptions and way of analysis, the model might have following weakness:

- Vehicle are simplified to types, rather than individuals with various deceleration rate, reaction time etc, and this could introduce errors and bias. Specifically, self-driving cars could have quite different reaction time, and even ways of avoiding collisions such as changing lanes. Drivers might have different reaction time due to mental states and focus differences. Some driver tends to keep larger than necessary safe-distance while others do not. If the estimates we use are not accurate enough, or do not capture large variance, stochastic models should be considered in stead.

- Since we implement LWR Models with Triangular Fundamental Diagram, our model bares all its draw-backs and inaccuracy as well.

Please note that this is likely not a complete list of weakness. Still, the model provides insights on how self-driving car taking less spaces of highway traffic, and dedicated lane might be an option once a larger proportion of traffic is self-driving cars.

6 Conclusions

- Current traffic demand well overload existing highways.
- Self-driving car are around 3 to 4 times more space efficient on highways. Therefore its adaption will greatly improve current highway situation.
- Dedicated Lane Policy:
  Approximately around 22% self-driving vehicle for 5-lane highway, 28% for 4-lane, 38% for 3-lane and 58% for 2-lane highway is required to add the first dedicated lane. Adding dedicated lane below these threshold will decrease highway capacity instead. These threshold should not be far from the true value, but can differ a bit as more self-driving car statics are obtained.

7 Further Works

- **Accident rate and traffic flow** Since self-driving car is yet a quite new technology, not enough data did we found to draw statistically significant conclusion regarding its accident rate. Additionally, many self-driving car companies claim that self-driving car are not at-fault in most accident involving them. If accident rate data of self-driving car is available, analysis of accident rate and traffic flow can be drawn to determine effects of self-driving car. This analysis would be quite meaningful since accidents do play great roles in jams.
- **Self-driving car and car-pool industry** For most of time, cars are parked rather than driven. Several families sharing a self-driving car could be in consideration. Also, serving as taxis, self-driving car in theory might be safer and cheaper. In these ways, self-driving car potentially allows more people to be

transported while less vehicle are on street. This yet to come industry could also lift the burden of traffic.

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Dear Government Officer,

The problem of traffic capacity has been discussed over years due to the limitation of the number of lanes in highways and the increasing rate of car ownership. The real problem is far beyond this. The increasing traffic flow over years could trigger more car accidents than before and the efficiency of highway will decrease at the same time. Thanks to the development of artificial intelligence, the emergence of self-driving car provides us a brand new idea for solving traffic problems. However, since this high-tech product has not yet been popularized and the technical and moral issues behind it are still widely discussed by the public, we should hold an optimistic but cautious attitude towards this exciting new product.

To begin with, we would like to enumerate the advantages of self-driving techniques which can later be served as good reasons for promoting the use of autonomous cars. First, the most tempting merit is its low accident rate,which has been confirmed by the study from many research institutions. Due to the effective algorithm and the accurate calculation made by the computer, the self-driving cars can detect dangers much more swiftly than the normal vehicles. Second, the self-driving vehicles can help to increase the high-way capacity and reduce the traffic congestion. If the information system of the self-driving vehicles is sophisticated enough and the communication between self-driving and non self-driving cars is stable, the self-driving cars can guide the normal cars behind to avoid the traffic jam during rush hours. Third, self-driving cars can help more people enjoy the convenient and safe traveling experience offered by the automobiles. For those senior citizens who originally don't go out very often due to the inconvenience of the transportation, self-driving cars can provide enormous assistance.

Nevertheless, everything has its drawbacks and the self-driving cars are no exception. We sincerely wish that before the real popularization of this new type of cars, you can continuously collect the required data and pay close attention to any noteworthy changes. Also, every time when a new policy is made, please first trial on a few routes before making the policy official. According to our VMT data, maybe testing on route SR-520 initially is a wise choice due to the smaller traffic amount. Meanwhile, legislation is also in urgent need during the procedure of policy making. The issues including who should be responsible for the traffic accidents and how to guarantee the quality of self-driving cars should all be considered.

Finally, we'd like to provide some suggestions according to the mathematical models we derived. First, according our models, the cooperation between self-driving cars and the interaction between self-driving and non-self-driving cars can significantly increase the maximum traffic capacity and the traffic efficiency. Thus, more money should be spent to support researchers on exploring new techniques of machine communication. Also, for the non-self-driving cars, advice of setting devices to receive information from self-driving automobiles should be given to the drivers. Second, according our study, we believe that if the percentage of self-driving cars is large enough, dedicating lanes to self-driving cars and increase the speed limit of that lane can be a good choice. Our study also indicates that when the percentage of self-driving cars is not large enough, dedicating lanes should be firstly applied to highway segments with larger number of lanes because doing the same thing to those with smaller amount of lanes can not increase the overall traffic performance. With the popularization of the self-driving cars, cost and benefit analysis should be conducted frequently to see whether it is necessary to dedicate lanes to self-driving cars for those segments with smaller amount of lanes.

Due to the limitation of time and information, our work is not complete. More efforts need to be dedicated to the study of this field and we'll keep on working on this painstakingly. We appreciate a lot for all your contributions to the country and we are looking forward to seeing more positive changes in the future. Thank you so much for reading the letter.

Sincerely,

MCM Team Members