Truck-platooning impacts on traffic

CIE5050-09: Additional Graduation Work, Research Project

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by

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1

Introduction

In this chapter, a brief background introduction is given. The literature about the impact of truck platooning is summarized.

1.1. Background

Autonomous vehicles have been developed for decades. Many well-established and relevant technologies are available. However, the application of the actual application of self-driving cars is still in its infancy. The impact of fully automated vehicles needs to be further explored. Real-life data are vital for building a more solid basement for the operation of vehicle automation technologies.

Adaptive cruise control(ACC) is one of the technologies already being used in many consumer-grade vehicles. The ACC allows the vehicle to automate the longitudinal driving task during the car following behavior and free driving behavior. And based on ACC, the CACC allows vehicles to communicate with other vehicles with short-range wireless communication[12]. Communication between vehicles can provide a more comfortable and safe driving experience, as the vehicle brakes much more softly[14]. To improve the efficiency of freight transport, the implementation of the CACC in trucks may be a suitable solution. With the ACC/CACC system, trucks can be operated as a platoon. The longitudinal behavior (both longitudinal and latitudinal for some platooning projects) is controlled by the automation system. Many studies have already been divided into the traffic flow effect of the ACC and CACC. The enabling of CACC is believed to improve traffic flow stability[6], safety, and infrastructure capacity[10] under certain conditions, and the results are based on simulation. Conclusions are drawn primarily by simulation and are mainly about passenger vehicles. Truck platooning is believed to have an effect on safety, fuel consumption, traffic efficiency, and comfort[3].

This research is carried out to determine the effect of truck platooning on traffic flow using empirical data. This research contains two parts, data fusion and statistical analysis. For data fusion, loop detector data, infrastructure information and weather data will be added to the original data set. For statistical analysis, the time gap distributions under different categories are analyzed to determine the performance of the truck platoon. Additionally, analysis of the lane change behavior and the reaction time of the platoon to congestion will also be analyzed.

1.2. Literature Review

The expected impact of the truck platoon can be summarized in four categories: safety, fuel consumption, traffic efficiency, and comfort[3].

As for the safety impact, it is believed that truck platooning results in a lower accident rate due to the higher automation level and the fact that most traffic accidents are caused by human errors[9]. There are also quantitative analyses of the truck safety impact. Two indicators are used to evaluate the safety aspect of truck platooning: the number of brake threats and the time-to-collision. The simulation result of Faber et al.[8], shows that truck platooning has a negative effect on traffic efficiency and safety when the density of the road is high. And their study also shows that the implementation of the truck platoon on the main road will decrease the efficiency and safety of the road, no matter if the traffic is high or low.

The two main factors that can cause danger during platoon driving are the cut-ins of the surrounding traffic and the hazard of a vehicle running into the preceding vehicle in the platoon[2].

Truck platooning also has a positive influence on fuel consumption. Due to the fact that one-quarter of the fuel consumption is related to aerodynamic drag, platooning driving could decrease the fuel consumption by reducing the air drag[15]. According to a field test done by Transport Canada's Motor Vehicle Test Centre[11], truck platooning has a fuel saving of 5.2% to 7.8% compared to three trucks traveling independently under certain conditions.

As for the traffic efficiency impact, there are different opinions. Many studies are already divided into the traffic flow effect of the ACC and CACC. The possible benefits of CACC could be the improvement in capacity, flow stability, and fuel consumption. Arem et al.[1] conclude that the CACC can improve traffic flow stability and slightly increase traffic flow efficiency under certain simulation conditions. An essential factor in the ACC/CACC application is the penetration rate. According to Arem et al.[1], the improvement in traffic flow is highly dependent on the penetration rate of CACC. A high penetration rate will result in an improvement in traffic throughput and a low penetration rate will even lead to performance degradation. VanderWerf et al.[13] used Monte Carlo simulations based on detailed models. The result of the simulation indicates that the ACC has a limited impact on traffic. And with the increase in penetration rate, the return rate is decreasing; there will be no capacity increase after 40% AACC. Another significant result is that CACC can potentially double the capacity of a highway lane at a high penetration rate. Calvert et al.[5] conducted research based on data collected in real traffic. The string stability of CACC driving is much better than that of ACC driving, and three-vehicle platoons were able to platoon longer than a seven-vehicle platoon. The result shows that it is possible to operate CACC vehicles on the (sub)urban arterial while ACC vehicles are unsuitable for this area. And because the penetration rate is too small for a field operational test, traffic flow improvements are difficult to derive.

Currently, the influence of vehicle platooning is primarily focused on passenger vehicles. However, there are also studies on the CACC truck application and the impact of truck platooning is different. The influence of the truck platoon on traffic flow should be considered in two parts, the longitudinal traffic flow effects and the lateral effects. Calvert et al.[4] have conducted an experiment to evaluate the traffic flow effects of truck platooning. The simulation result shows that the negative influence on traffic flow performance is small when traffic demand is less than 80% of the capacity. However, a large negative effect was found in the congestion scenario. They suggested that truck platooning should be restricted to traffic states that are not near congested or congested.

Truck platooning is believed to have an impact on different aspects and the impacts of the ACC system and the CACC system are different. In this research, real-life truck platoon data are used to draw a more specific conclusion on the different impacts of ACC and CACC under different conditions.

2

Research Methodology

In this chapter, the available data and the methods that are used to explore the real-life experiment of truck platooning and its impact on the surrounding traffic are introduced. This method consists of two steps: 1) data fusion and 2) statistical analysis.

2.1. Data description

The data come from a real-life truck platooning pilot(Ursa Major neo Truck Platooning Trial) that was executed from June to July in The Netherlands. The truck platooning trial is on the motorway along the Rotterdam - Venlo corridor. This route passes the A15 / A16 / A58 / A2 / A67 motorways and partially overlaps with the Rhine-Alpine corridor within the Trans-European Transport Network. The controller types and the controller time gaps are varied. These data will be collected by different types of sensors.

The data that will be used can be divided into two parts. The first part is the truck platoon trial data, and the second part is the data from other sources. The other available data will be used as a supplement to the trial data and add value to the trial data. The data are provided in a complex nested mat file. The structure of the mat file is shown in Figure 2.1.

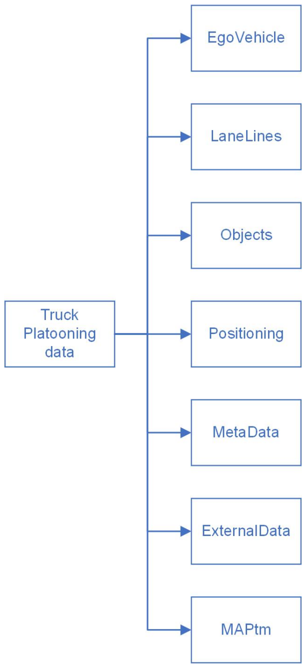

Figure 2.1: Data structure

The data mainly consist of seven parts, the Ego vehicle data, lane and lines, positioning, meta data, external data, and MAPtm data. For each struct array, there are several subarrays. The first struct array is the ego vehicle; this array contains the status of the ego vehicle. And the Lanelines contains information about the lane. The objects contains the platoon information. The positioning provides the GPS position data. The MateData contains the setting of each experiment. The external data are about the type of road. And the MAPtm data mainly include the speed and flow information of the road.

Data collection dates are shown in table 2.1.

Table 2.1: Dates of data collection

1	1-6-2022
2	15-6-2022
3	16-6-2022
4	20-6-2022
5	24-6-2022
6	28-6-2022
7	29-6-2022
8	1-7-2022
9	6-7-2022
10	8-7-2022
11	15-7-2022
12	20-7-2022
13	21-7-2022
14	22-7-2022
15	29-7-2022
16	10-8-2022
17	22-8-2022

For each day, two different experiment sets of data are collected(et_2 and et_3). The data about the ego vehicle is collected per 0.1s.

2.2. Analysis methods

2.2.1. Data Fusion

One of the main parts of this research is to attach data from other sources to truck platoon data. Here, two types of data are available and suitable for attachment to the trial data: loop detector data and infrastructure information. Loop detector data can provide us with the speed and flow of a certain route over a certain period. This can help to analyze the interaction between the truck platoon and the traffic environment. There may be a difference in the performance of the truck platoon under different traffic conditions.

The type of infrastructure can also influence the performance of the trucks. With information on road infrastructure, one can analyze the time gap distribution of trucks under different types of roads. A more comprehensive traffic impact of truck platooning can be analyzed. The infrastructure information that is used comes from the open street map.

2.2.2. Statistical analysis

fundamental diagram

To decide the categories of traffic conditions, the fundamental diagrams have to be estimated. All parts of the road are the motorway. Due to the good consistency of the route; it can be assumed that the fundamental diagram of each part of the road is similar. Here, we assume a triangular fundamental diagram. The jam density and the free flow speed are fixed. Here, only the critical density is estimated using the flow and speed data. Find the critical density that gives the minimum sum of squared differences.

Time gap distribution

The time gap distribution under different categories(congested/uncongested, weaving section/not weaving section, etc.) will be plotted. The distribution might help to analyze the performance change of the truck platoon between different traffic conditions and between different types of roads.

Time-gap distributions are considered among different traffic states, as the performance and impact of the truck platooning might be different when the traffic flow of the road is different. As for the road types, the weaving sections, tunnels&bridges, and regular motorways are considered to investigate the performance difference.

Different categories can also be used to calculate indicators to investigate performance differences under different traffic conditions further. And to ensure there is a statistical difference between the two distributions, the Two-sample Kolmogorov-Smirnov Test is used to test whether the distributions of the two samples are similar or not. The K-S test checks whether the two distributions are similar or not by generating the cumulative figures and finding the largest distance along the y-axis. The statistical value of K-S test is:

$$D_{m,n} = \max_x |F_m(x) - F_n(x)|$$

Where $F_m(x)$ is the first sample and the size of the sample is m. $F_n(x)$ is the second sample, the size is n. The $c(\alpha)$ is the inverse of the Kolmogorov distribution at α. The null hypothesis is that both samples are from the same distribution. The $D_{m,n,\alpha}$ is calculated by the following equation:

$$D_{m,n,\alpha} = c(\alpha)\sqrt{\frac{m+n}{mn}}$$

And if the statistical value $D_{m,n}$ is bigger than $D_{m,n,\alpha}$, we can reject the null hypothesis at a significant level α. If not, we can not reject the null hypothesis which means that the two distributions are probably the same.

Acceleration Distribution

The acceleration distribution is another part of the analysis. The shape of cumulative distribution curves could help to explore the difference in acceleration and deceleration rates between manual driving, ACC, and CACC.

lane changing analysis

The lane-changing behavior is also an important part of this data analysis. First, detect lane change maneuvers during the trial. Here, the maneuvering behavior is detected using the steering angle of the leading truck. During the lane change behavior, the shape of the steering angle should look like a sine function or cosine function. According to Esmaeili et al.[7], at 60km/h the peak of steering angle during the lane change process should be about 3 degrees and the lane change behavior should last 30 seconds. Then the gap distributions during the maneuvering behavior and not during the maneuvering behavior are compared.

3

Analysis Result

In this chapter, the result of the data fusion and the result of statistical analysis are elaborated.The conclusion on the different impacts of ACC and CACC under different conditions are drawn.

3.1. Data Fusion Result

3.1.1. loop detector data

The trial data contains the latitudes and longitudes of the trucks. With these coordinates, the speed and flow of the surrounding vehicles can be attached to the trial data. NDW loop detector data are available.

The first step is to generate the geojson files that are required to request the NDW loop detector data. The geojson file contains the route coordinates. Since too many coordinates are included in the truck-platooning data, one coordinate per 100 points is chosen to generate the route in the geojson file. Then use the API to request the loop detector data for each experiment period.

NDW loop detector data contain speed and traffic flow information with an interval of 1 min. The structure of the NDW loop detector data is shown in Figure 3.1.

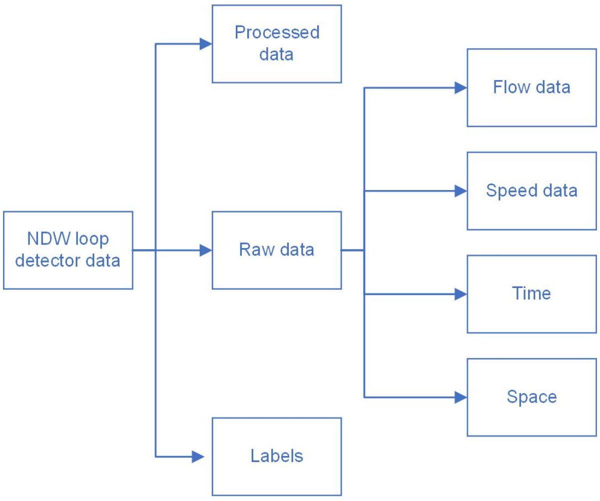

Figure 3.1: Structure of the NDW loop detector data

The flow data are stored as a two-dimensional array. The two dimensions are time and space. The space(position of the loop detector) and the time are stored in two one-dimensional arrays. The unit flow is veh / h / lane and the unit speed is km / h. There are processed data and raw data. To obtain a more accurate result, raw data are used. To obtain the state of surrounding traffic, the NDW data must be matched to the truck platooning trial data. The data attachment method is shown in Figure 3.2.

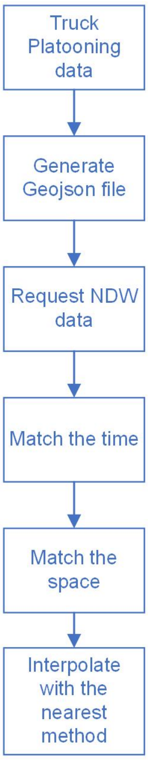

Figure 3.2: Loop detector data attachment method

The first step is to request the NDW loop detector data. The information that is needed to request the data is the geojson file, which contains the coordinates of the selecting route. The coordinates from the truck platoon trial are used to generate the geojson file. After requesting the loop detector data, the next step is to attach the data according to time and distance. After transposing the speed array in the NDW data set, create a new list with the same length of the UTC time in the truck platoon data. Assign each row in the speed array to the new list when the time matches. Then match the space using the distance on the odometer. Since the interval of the NDW speed data is 1 min and the interval of the truck platooning data is quite small, it is necessary to interpolate the empty speed value with the nearest value. The NDW data for 2022-09-21 is not available. The attachment of flow data followed the same process.

The results of the attachment are shown in Figure 3.3 and Figure 3.4.

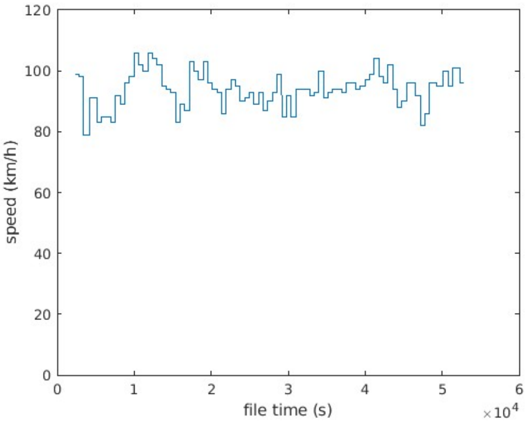

Figure 3.3: Speed of the surrounding vehicles of et2 2022-07-22_A16toRdam_conditionB5

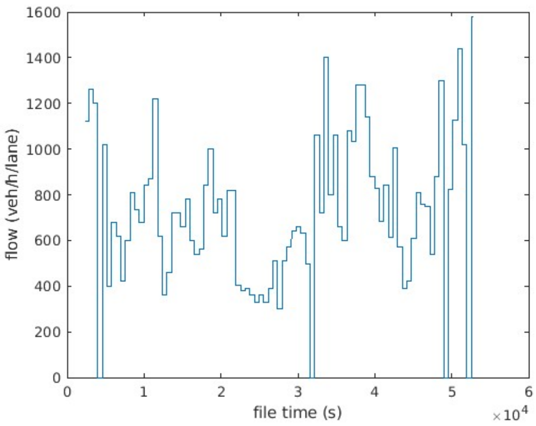

Figure 3.4: Flow of the surrounding vehicles of et2 2022-07-22_A16toRdam_conditionB5

3.1.2. infrastructure information

Another thing that can be added to the truck platooning data is infrastructure information. The performance of the truck platoon can vary depending on the different types of roads. Here, three types of roads are specified: waving sections, bridges, and regular motorways.

The attachment method consists of two different parts: identification and attachment. The first part is to identify and obtain the coordinates of all the weaving sections/bridges along the route. For bridges, the method is to manually select the bridges and save the coordinates. For the weaving section, open-street map data are used. The identification process is shown in Figure 3.5.

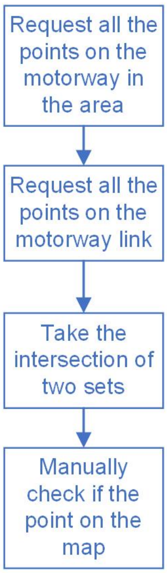

Figure 3.5: Ramps identification

The overpass turbo is used to request and process the data. To obtain the coordinates of all the ramps, the first step is to obtain all the points on the polyline of the motorway in a selected area. Then request all the points on the links to the motorway. The intersections of the two sets will be all the points of the on-ramps and off-ramps. Then manually check the set and save only the points along the route.

The next step is to match the coordinates of all the on-ramps/off-ramps. The latitude and longitude of the trucks for each time step are given. For all the points in the ramps list, calculate the distance between the ramp and the location of the trucks. Find the minimum value; If the minimum distance is shorter than 3 meters, the trucks have passed this ramp. Then, detect the weaving section using the result of the last step. If the distance between an on-ramp and an off-ramp is shorter than 500 meters, it is considered a weaving section.

The attached weaving section is shown in Figure 3.6.

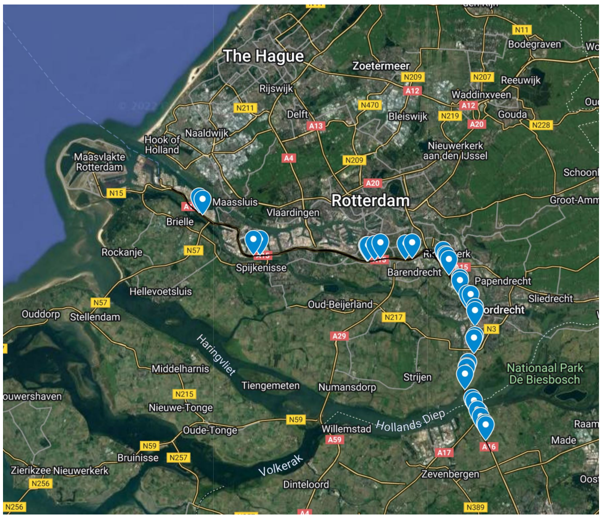

Figure 3.6: Weaving sections of et2 2022-07-22_A16toRdam_conditionB5

The attachment method of the bridges is similar.

3.2. Fundamental diagram estimation

The flow and density data from the loop detector of one day are used to estimate the fundamental diagram. In Figure 3.7, it can be observed that when the value of critical density is 29 veh/km the sum of squared differences is at minimum.

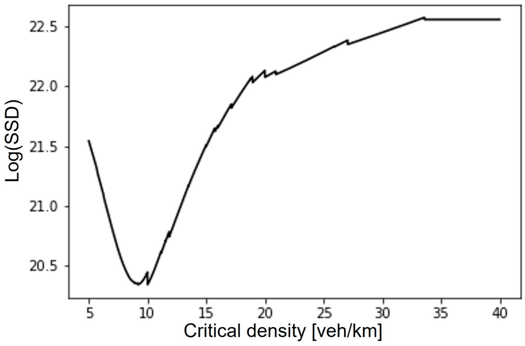

Figure 3.7: SSD for different k^{cr}

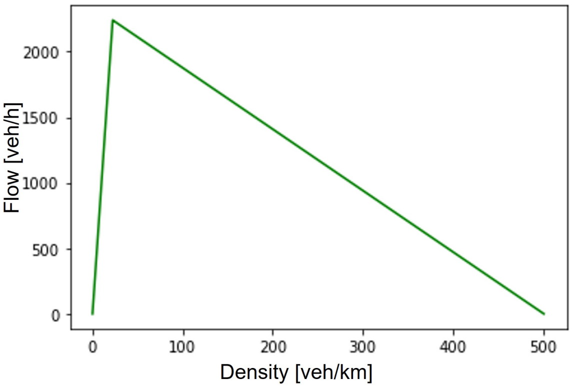

Figure 3.8: Estimated FD

With the critical density and the other assumed parameters, the Fundamental diagram can be drawn, and the FD of the motorway is shown in Figure 3.8. The critical density is relatively low because the high density or congested sample is relatively small. The result of the fundamental will be helpful in the further analysis step. The categories of traffic conditions in the time-gap distribution are mainly based on the fundamental diagram. The result of the FD estimation is only used to categorize the traffic condition during further analysis steps.Therefore, the result does not need to be so accurate.

3.3. Time-gap distribution among different traffic states

As shown in the previous section, only the space gaps between the ego vehicle and the follower are given in the data set. The time gaps are calculated with the following equation:

$$Time\_gap = \frac{LongPosition - 2.5m}{V_{follower}}$$

LongPosition is the relative position collected by the MIO. 2.5m is the distance between the sensor and the front bumper, $V_{follower}$ is the speed of the follower.

Then the time gap distributions among different traffic states are shown in Figure 3.9.

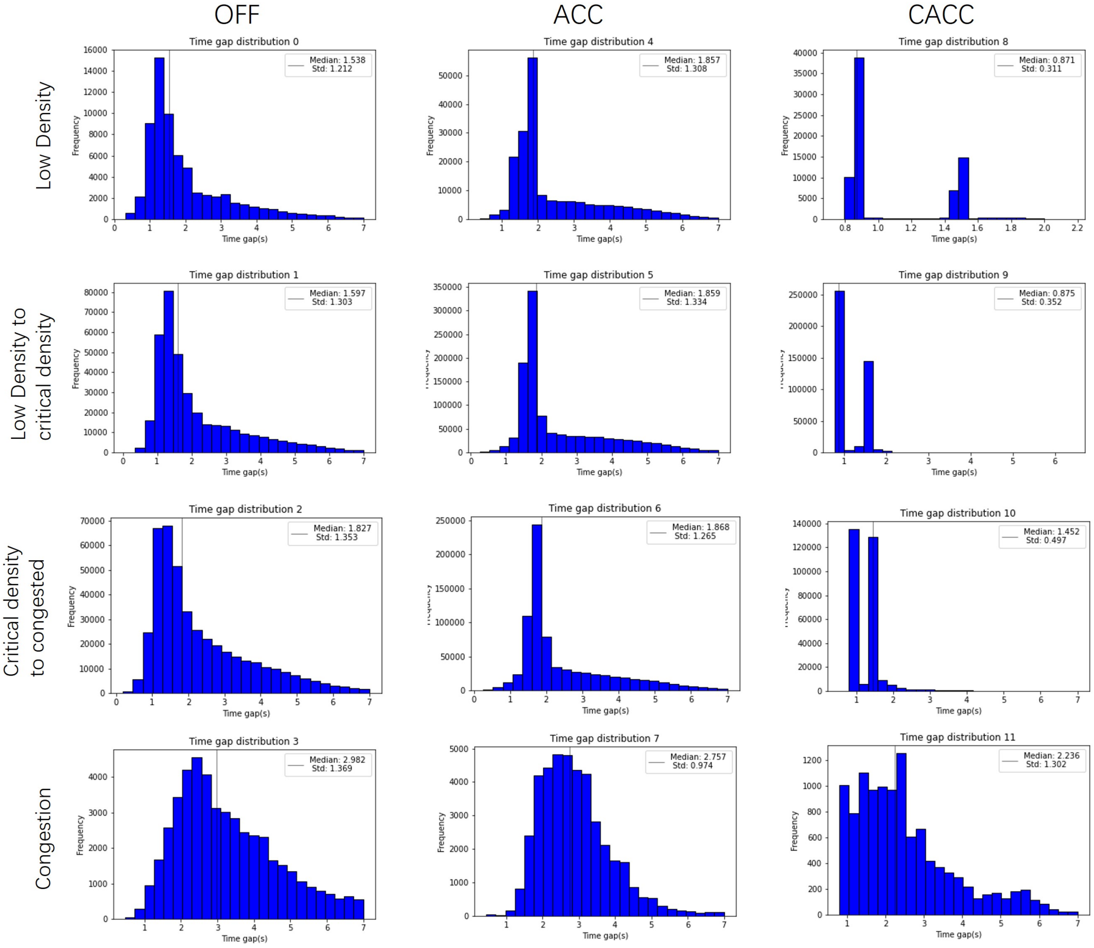

Figure 3.9: Time-gap distributions among different traffic states

The distribution figures are based on the density of the road. Four categories are low-density, low-density to critical-density, critical density to congestion, and congested-density. For each figure, the median is calculated to represent the overall situation of the time-gap distribution. Standard deviation is used to represent the stability of the driving process. The Two-sample Kolmogorov-Smirnov Test is used to test if the two distributions are similar. Some of the results are shown in Table 3.1.

Table 3.1: Two-sample Kolmogorov-Smirnov Test result

Sample 1	Sample 2	Statistic	P-value
OFF(Low density)	OFF(Low density to critical density)	0.043344	6.13E-93
OFF(Low density)	OFF(Critical density to congestion)	0.129564	0
OFF(Low density)	OFF(Congestion)	0.49578	0
OFF(Low density)	ACC(Low density)	0.348355	0
OFF(Low density)	ACC(Low density to critical density)	0.352749	0
OFF(Low density)	ACC(Critical density to congestion)	0.349163	0
OFF(Low density)	ACC(Congestion)	0.506405	0
OFF(Low density)	CACC(Low density)	0.59203	0
OFF(Low density)	CACC(Low density to critical density)	0.539214	0
OFF(Low density)	CACC(Critical density to congestion)	0.410032	0

OFF(Low density)	CACC(Congestion)	0.264287	0
OFF(Low density to critical density)	OFF(Critical density to congestion)	0.099438	0
OFF(Low density to critical density)	OFF(Congestion)	0.460963	0
OFF(Low density to critical density)	ACC(Low density)	0.318235	0

Compare the p-value with the significance level $\alpha = 0.01$; if the p-value is higher than α, then the two distributions are probably the same distribution, then there is no statistical difference between the two samples. If the p-value is lower than α, the two samples are from two different distributions which indicates that there is a performance difference between the two categories. From table 3.1, it can be observed that all the distributions are different(the p-values are all smaller than 0.01). Performance differences exist between the modes. And for the same mode, the performance of the system is different under different traffic conditions. For all other test results, no p-value is larger than 0.01, which means that there are no similar time gap distributions.

Then the performance difference can be concluded from the median and standard deviation of the distributions. When the driving mode is manual driving, the distribution figures are quite similar. The median of the time gaps is near 1.5s for uncongested traffic. The median of the time-gap distribution is 1.827s. This means that the overall time gap is larger. When in congestion, the median of the time gap increased to 2.982s and the standard deviation is smaller, which means that the time gaps are more average distributed. When manually driving, the driver will keep the space headway not shorter than a certain distance, even if the speed is very slow. Thus, when in congestion, the space headway did not vary much; the speed changed within a certain boundary, which results in a more even distribution of time gap.

For the ACC mode, the simulation is quite similar. The median is about 1.8. Since the time gap settings of the ACC driving mode is 1.5s and 2.0s, most of the data points are within this range. There are also some points where the ACC failed to maintain the time gap. The percentage of these points is higher for the higher density category; since the standard deviation of the time-gap distribution 6 is higher than the time-gap distributions 5 and 4. In terms of the high-density situation, the median is larger and the standard deviation is smaller. In a congested situation, the ACC will also try to maintain a fixed safety distance. For the same reason as manually driving, the distribution is more even.

In terms of the CACC driving mode, the low density distribution has a fairly small standard deviation, which means that the CACC system performed better in maintenance of time gaps. It can be observed that there are two clusters of time gaps. Since the time gap settings of the CACC are 1s and 1.5s, the two clusters are close to 1.0s and 1.5s. When the density is high, the standard deviation increases. The CACC has pretty good performance, and the time gap is stable when the density is low. When the density of the road is high, the CACC sometimes failed to maintain the time gap, so the std is much larger.

Since there are different time gap settings during the trial, the time gap needs to be specified to draw a further conclusion. The median and standard deviation of the ACC and CACC with different gap settings are shown in Table 3.2.

Table 3.2: Result under different time gap settings

		ACC			CACC		
		setting 1	setting 2	setting 3	setting 1	setting 2	setting 3
Low Density	Median	1.8317	1.6420	1.8710	0.8626	1.2780	1.4898
	Std	1.4949	1.2909	1.2149	0.1118	0.0749	0.0890
Low Density to critical density	Median	1.9372	1.6566	1.8681	0.8637	1.2581	1.4902
	Std	1.4881	1.3272	1.2435	0.2148	0.1655	0.1177
Critical density to congested	Median	1.8228	1.6935	1.8796	0.8644	1.4449	1.4923
	Std	1.4472	1.3037	1.1597	0.4648	0.2751	0.3232
Congestion	Median	2.0039	2.9785	2.4236	1.3019		2.5484
	Std	0.9096	0.9706	0.8617	0.7210		1.2123

Conduct the K-S test for every two distributions. Part of the result is shown in Table 3.3.

Table 3.3: Two-sample Kolmogorov-Smirnov Test result

Sample 1		Sample 2		Statistic	P-value
OFF(Low density)	setting 1	OFF(Low density)	setting 2	0.036946	1.05E-47
OFF(Low density)	setting 1	OFF(Low density)	setting 3	0.046717	1.63E-69
OFF(Low density)	setting 1	OFF(Low density to critical density)	setting 1	0.374576	1.61E-273
OFF(Low density)	setting 1	OFF(Low density to critical density)	setting 2	0.944395	0
OFF(Low density)	setting 1	OFF(Low density to critical density)	setting 3	0.936947	0
OFF(Low density)	setting 1	OFF(Critical density to congestion)	setting 1	0.870351	0
OFF(Low density)	setting 1	OFF(Critical density to congestion)	setting 2	0.486293	0
OFF(Low density)	setting 1	OFF(Critical density to congestion)	setting 3	0.401876	0
OFF(Low density)	setting 1	OFF(Congestion)	setting 1	0.400324	0
OFF(Low density)	setting 1	OFF(Congestion)	setting 2	0.382469	0
OFF(Low density)	setting 1	OFF(Congestion)	setting 3	0.440428	0
OFF(Low density)	setting 1	ACC(Low density)	setting 1	0.572215	5.77E-30
OFF(Low density)	setting 1	ACC(Low density)	setting 2	0.596263	6.93E-297
ACC(Congestion)	setting 3	OFF(Critical density to congestion)	setting 2	0.808951	1

There is only one pair that does not pass the K-S test; the time gap distribution of ACC when in congestion (gap setting = 1.5 s) and the time gap distribution of CACC when in congestion(gap setting = 1.5s). This result indicates that there is no performance difference between ACC and CACC during congestion traffic, although the median and standard deviation of ACC are smaller.

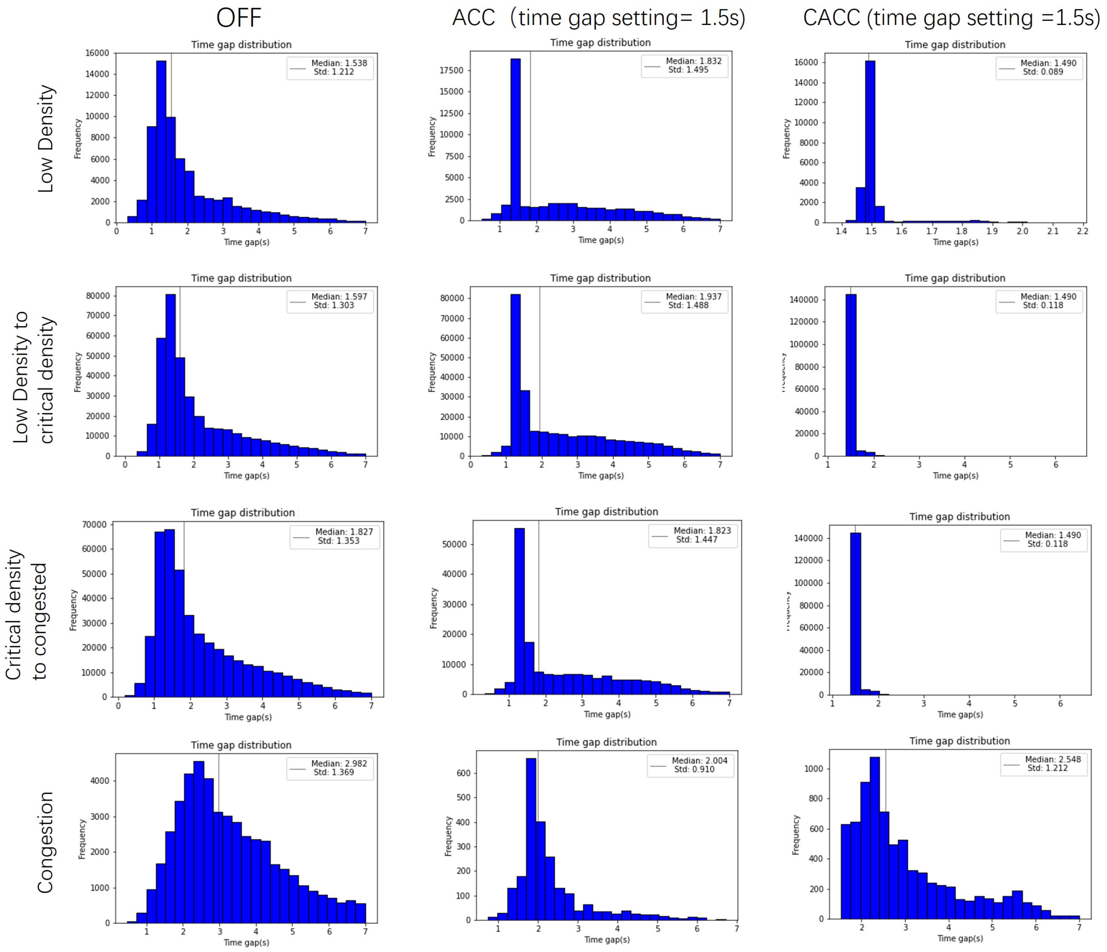

Figure 3.10: Time-gap distributions among different traffic states(time-gap setting = 1.5s)

When the density is low, the standard deviation of CACC is much smaller and the median is quite close to the time gap setting. The same thing happened when density is high. It can be concluded that the CACC performs better when not in congestion. While the traffic is congested, there will be no performance difference anymore. By comparing the standard deviation of manual driving and the ACC, it can be observed that manual driving performs better in maintaining time-gap when traffic is not congested. Manual driving can keep the time gap within a specific boundary, while there the time gap for maintaining failure is more evenly distributed.

3.4. Time-gap distribution among different infrustracture

The time-gap distributions among different types of roads are shown in Figure 3.11.

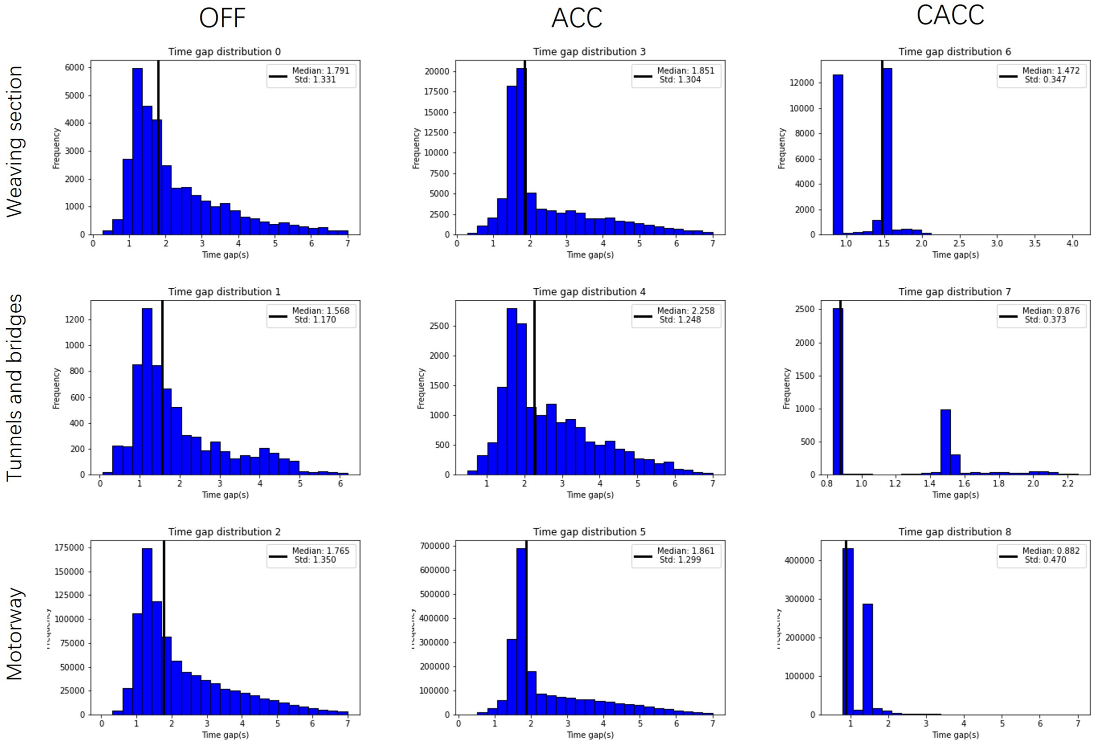

Figure 3.11: Time-gap distributions among different road types

The result of the K-S test shows that the time gap sample of manual driving and CACC while driving is likely from the same distribution. It can be concluded that there is no performance difference between manual driving and CACC in tunnels and bridges.

Table 3.4: Two-sample Kolmogorov-Smirnov Test result

Sample 1	Sample 2	Statistic	P-value
OFF(Weaving section)	OFF(Tunnels and bridges)	0.14561	2.64E-107
OFF(Weaving section)	OFF(Motorway)	0.034369	1.54E-33
OFF(Weaving section)	ACC(Weaving section)	0.199261	0
OFF(Weaving section)	ACC(Tunnels and bridges)	0.250127	0
OFF(Weaving section)	ACC(Motorway)	0.232704	0
OFF(Weaving section)	CACC(Weaving section)	0.56401	0
OFF(Weaving section)	CACC(Tunnels and bridges)	0.549537	0
OFF(Weaving section)	CACC(Motorway)	0.565282	0
OFF(Tunnels and bridges)	OFF(Weaving section)	0.14561	2.64E-107
OFF(Tunnels and bridges)	OFF(Motorway)	0.12959	7.72E-102
OFF(Tunnels and bridges)	ACC(Weaving section)	0.320905	0

OFF(Tunnels and bridges)	ACC(Tunnels and bridges)	0.368541	0
OFF(Tunnels and bridges)	ACC(Motorway)	0.353998	0
OFF(Tunnels and bridges)	CACC(Tunnels and bridges)	0.500954	1

For manual driving, there is no major difference between the three types of roads. The median of time gaps in the tunnels is smaller. And the standard deviation during tunnels and bridges is minor. For the ACC driving mode, the peak of driving on the motorway is much higher, and this indicates that the ACC system performs better compared to driving in the weaving sections or tunnels. However, there are different time gap settings during the process; the time gap settings need to be specified before drawing any further conclusion. AS for CACC, the two time-gap settings can be observed from all the distribution figures. And the standard deviation is much smaller compared to manual driving or ACC.

To further compare the time-gap distribution between different driving modes, the time gap during the setting is 1.5 seconds of ACC and CACC are selected. The standard deviation and median of the categories with different gap settings are shown in Table 3.5.

Table 3.5: Result under different time gap settings

		ACC			CACC		
		setting 1	setting 2	setting 3	setting 1	setting 2	setting 3
Weaving sections	Median	1.6829	1.6457	1.8657	0.8648	1.3318	1.4918
	Std	1.4735	1.2911	1.2356	0.1214	0.2143	0.1584
Tunnels and bridges	Median	2.3672	2.0888	2.2406	0.8636		1.5069
	Std	1.2579	1.4038	1.1789	0.2257		0.1729
Motorway	Median	1.8884	1.6644	1.8733	0.8639	1.2786	1.4913
	Std	1.4732	1.3001	1.2025	0.3278	0.2738	0.3754

And the distributions of the time gap setting equal to 1.5s are shown in Figure 3.12.

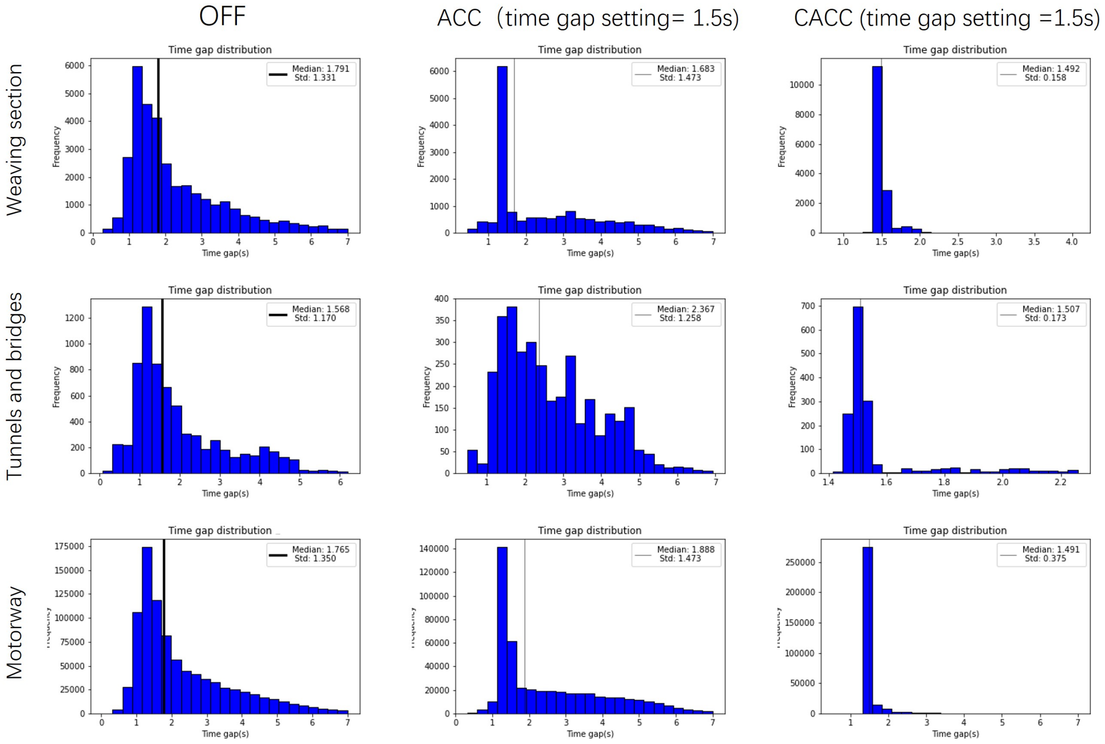

Figure 3.12: Time-gap distributions among different road types(time-gap setting = 1.5s)

The results of the K-S test are shown in Table 3.6.

Table 3.6: Two-sample Kolmogorov-Smirnov Test result

Sample 1		Sample 2		Statistic	P-value
OFF(Weaving section)	setting 1	OFF(Weaving section)	setting 2	0.277976785	7.02E-193
OFF(Weaving section)	setting 1	OFF(Weaving section)	setting 3	0.047429519	6.84E-30
OFF(Weaving section)	setting 1	OFF(Tunnels and bridges)	setting 1	0.903727694	0
OFF(Weaving section)	setting 1	OFF(Tunnels and bridges)	setting 2	0.884911926	0
OFF(Weaving section)	setting 1	OFF(Tunnels and bridges)	setting 3	0.886242436	0
OFF(Weaving section)	setting 1	OFF(Motorway)	setting 1	0.371926278	0
OFF(Weaving section)	setting 1	OFF(Motorway)	setting 2	0.286863348	1.05E-220
OFF(Weaving section)	setting 1	OFF(Motorway)	setting 3	0.405073437	0
OFF(Weaving section)	setting 1	ACC(Weaving section)	setting 1	0.572833001	2.27E-16
OFF(Weaving section)	setting 1	ACC(Weaving section)	setting 3	0.466356685	0
OFF(Weaving section)	setting 1	ACC(Tunnels and bridges)	setting 1	0.36769519	0
OFF(Weaving section)	setting 1	ACC(Tunnels and bridges)	setting 2	0.395015525	0
OFF(Weaving section)	setting 1	ACC(Tunnels and bridges)	setting 3	0.421947766	0
OFF(Weaving section)	setting 1	ACC(Motorway)	setting 1	0.451609631	0

All pairs pass the test, which means that there are statistical differences between any two distributions. For all three categories, the CACC performs better in time gap maintenance than the ACC driving mode. The percentage of maintenance failure of the CACC (tunnels and bridges) is higher than in the weaving section and the regular motorway. This conclusion also holds for the ACC driving mode. There are more maintenance failures of ACC while driving in tunnels or bridges compared to other road types. The reason could be tested with a further experiment.

3.5. Acceleration distribution

The cumulative distribution functions of acceleration are shown in Figure 3.13. And the CDFs of deceleration are shown in Figure 3.14.

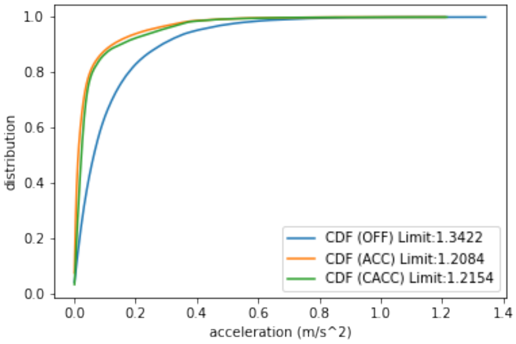

Figure 3.13: Cumulative distribution functions of acceleration

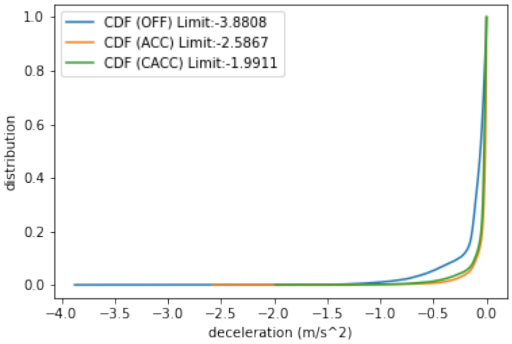

Figure 3.14: Cumulative distribution functions of deceleration

The shape of the CDFs are quite similar. However, it can be observed that the curves of ACC and CACC are steeper. The steeper cdf means that acceleration and deceleration are within a smaller scope. The acceleration CDF and deceleration CDF of ACC and CACC are much steeper than the manual driving CDF, indicating that the experience of driving in a truck platoon with ACC or CACC is better. It is safer for the vehicle behind the CACC truck platoon compared to following the manual driving trucks or ACC platoon since there is no extreme braking(the limit of CACC is smaller).

3.6. Maneuvering behavior

The lane-changing behavior is In the truck platooning trial, most of the maneuvering behaviors are performed to follow the route. Before executing the lane-change behavior, the driver needs to consider whether to accept the gap. Since gap data are unavailable, the gap within the truck platoon can be used to analyze the overall impact of the truck platoon on traffic flow. A larger gap means that the platoon will need more space to change lanes, which indicates a more profound negative impact on the traffic flow. The gap distributions of the maneuvering are shown in Figure 3.15, Figure 3.17 and Figure 3.19.

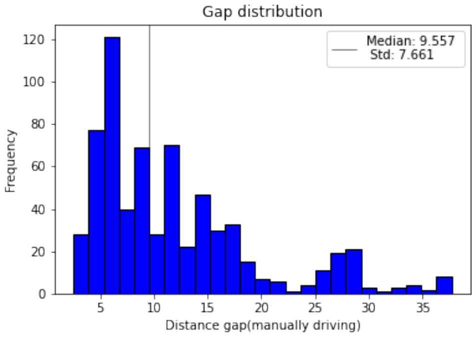

Figure 3.15: Gap distribution of manual driving (during maneuvering)

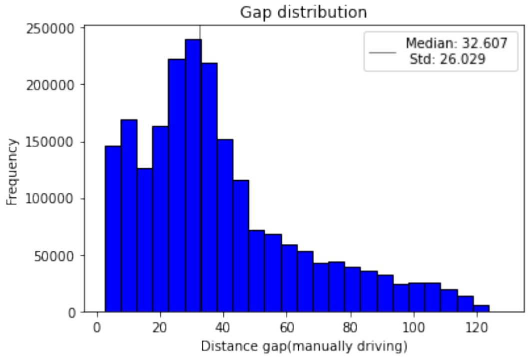

Figure 3.16: Gap distribution of manual driving

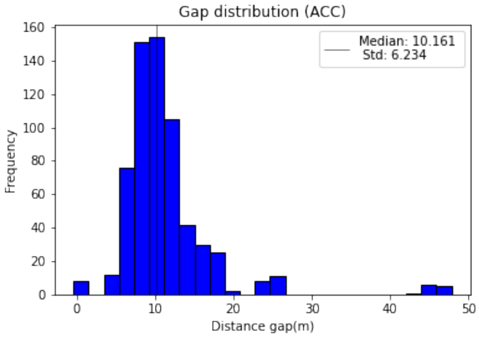

Figure 3.17: Gap distribution of ACC (during maneuvering)

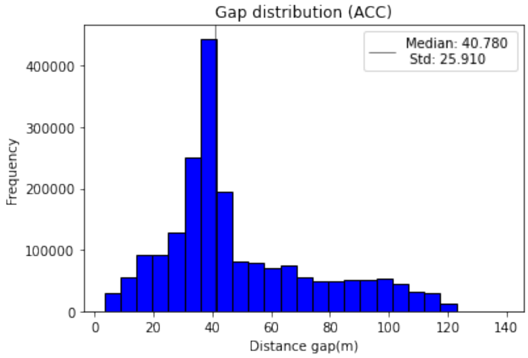

Figure 3.18: Gap distribution of ACC

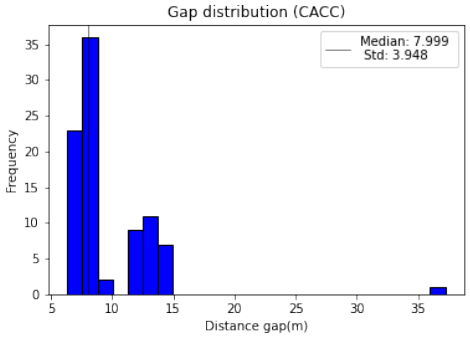

Figure 3.19: Gap distribution of CACC (during maneuvering)

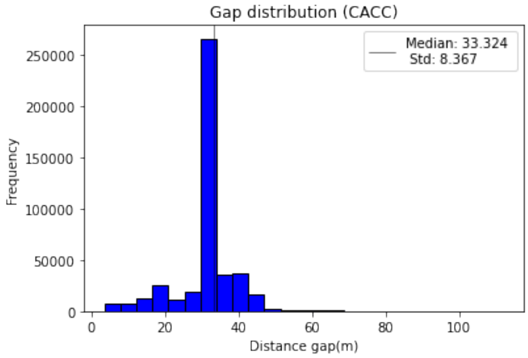

Figure 3.20: Gap distribution of CACC

Conduct the K-S test between the gap distribution while maneuvering and while not maneuvering (the steering angle is small); the results are shown in Table 3.7. The results indicate that the difference between the gap distributions while maneuvering and while not maneuvering is significant.

Table 3.7: Two-sample Kolmogorov-Smirnov Test result

	Statistic	P-value
Manual driving	0.64273	5.1429E-270
ACC	0.87976	0
CACC	0.94436	4.3543E-112

It can be observed that the CACC system can maintain a relatively small gap during lane-changing behaviors, and the gaps are more centrally distributed for the CACC system. This result indicates that the CACC truck platoon performs better than ACC and manual driving. The lane-changing behaviors of the CACC truck platoon are less likely to have a negative effect on traffic flow, since the platoon occupies less space in the longitudinal direction. There are no significant differences in the median and standard deviation between ACC and manual driving. This indicates that ACC could not improve the negative effect of lane change behavior compared to manual driving.

4

Conclusion and Future work

In this chapter the conclusion of the analysis is summarized. And the future work is elaborated.

In this project, real-life truck platooning data are analyzed. The analysis focuses mainly on the distributions of the time gaps under different traffic conditions and road categories. The Two-sample Kolmogorov-Smirnov Test is used to verify the statistical difference between two distributions. On the basis of the empirical data, it can be concluded that there is no performance difference between ACC and CACC during congestion traffic. And the CACC performs better in time gap maintenance when traffic is not congested. And the maintenance failure rate in the tunnels or on the bridges is higher for both the ACC driving mode and the CACC driving mode.

The other two parts of the statistical analysis relate to the acceleration distribution and the maneuvering behavior. From the acceleration/deceleration distribution plots, the distribution of the CACC driving mode is within a smaller boundary; there is no sudden breaking. The driving experience of the truck platoon with the CACC system is better compared to manual driving or ACC. And from the result of maneuvering behavior analysis, the CACC system could help to maintain a relatively small gap during lane changes. And ACC could not improve the negative effect of lane change behavior compared to manual driving.

All conclusions are drawn based on empirical data; to specify the reasons further, a simulation model could be built. And the empirical data could also help to calibrate the model. With the model, more detailed conclusions can be drawn. For example, the impact of longer truck platoons or any other conditions that are pretty hard to implement in real-life trials. And the influence of different penetration rates could be explored.

References

[1] Bart van Arem, Cornelie J. G. van Driel, and Ruben Visser. “The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics”. In: *IEEE Transactions on Intelligent Transportation Systems* 7.4 (2006), pp. 429–436. DOI: `10.1109/TITS.2006.884615`.

[2] Jakob Axelsson. “Safety in Vehicle Platooning: A Systematic Literature Review”. In: *IEEE Transactions on Intelligent Transportation Systems* 18.5 (2017), pp. 1033–1045. DOI: `10.1109/TITS.2016.2598873`.

[3] Carl Bergenhem et al. “Overview of platooning systems”. In: *Proceedings of the 19th ITS World Congress, Oct 22-26, Vienna, Austria (2012)*. 2012.

[4] S.C. Calvert, W.J. Schakel, and B. van Arem. “Evaluation and modelling of the traffic flow effects of truck platooning”. In: *Transportation Research Part C: Emerging Technologies* 105 (2019), pp. 1–22. ISSN: 0968-090X. DOI: `https://doi.org/10.1016/j.trc.2019.05.019`. URL: `https://www.sciencedirect.com/science/article/pii/S0968090X18303000`.

[5] Simeon C. Calvert and Bart van Arem. “Cooperative adaptive cruise control and intelligent traffic signal interaction: A field operational test with platooning on a suburban arterial in real traffic”. English. In: *IET Intelligent Transport Systems* 14.12 (2020), pp. 1665–1672. ISSN: 1751-956X. DOI: `10.1049/iet-its.2019.0742`.

[6] Anargiros I. Delis, Ioannis K. Nikolos, and Markos Papageorgiou. “Simulation of the penetration rate effects of ACC and CACC on macroscopic traffic dynamics”. In: *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. 2016, pp. 336–341. DOI: `10.1109/ITSC.2016.7795576`.

[7] Naser Esmaeili, Reza Kazemi, and S Hamed Tabatabaei Oreh. “An adaptive sliding mode controller for the lateral control of articulated long vehicles”. In: *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics* 233.3 (2019), pp. 487–515.

[8] Timo Faber et al. “Evaluating Traffic Efficiency and Safety by Varying Truck Platoon Characteristics in a Critical Traffic Situation”. In: *Transportation Research Record* 2674.10 (2020), pp. 525–547. DOI: `10.1177/0361198120935443`. eprint: `https://doi.org/10.1177/0361198120935443`. URL: `https://doi.org/10.1177/0361198120935443`.

[9] Robbert Janssen et al. “Truck platooning”. In: *Driving the* (2015).

[10] Hao Liu et al. “Impact of cooperative adaptive cruise control on multilane freeway merge capacity”. In: *Journal of Intelligent Transportation Systems* 22.3 (2018), pp. 263–275. DOI: `10.1080/15472450.2018.1438275`. eprint: `https://doi.org/10.1080/15472450.2018.1438275`. URL: `https://doi.org/10.1080/15472450.2018.1438275`.

[11] Brian McAuliffe et al. “Fuel-economy testing of a three-vehicle truck platooning system”. In: (2017).

[12] Jeroen Ploeg et al. “Design and experimental evaluation of cooperative adaptive cruise control”. In: *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*. IEEE. 2011, pp. 260–265.

[13] Joel Vander Werf et al. “Effects of Adaptive Cruise Control Systems on Highway Traffic Flow Capacity”. In: *Transportation Research Record* 1800.1 (2002), pp. 78–84. DOI: `10.3141/1800-10`. eprint: `https://doi.org/10.3141/1800-10`. URL: `https://doi.org/10.3141/1800-10`.

[14] Qing Xu and R. Sengupta. “Simulation, analysis, and comparison of ACC and CACC in highway merging control”. In: *IEEE IV2003 Intelligent Vehicles Symposium. Proceedings (Cat. No.03TH8683)*. 2003, pp. 237–242. DOI: `10.1109/IVS.2003.1212915`.

[15] Linlin Zhang et al. “Fuel economy in truck platooning: A literature overview and directions for future research”. In: *Journal of Advanced Transportation* 2020 (2020).