Conceptual Analysis of an AD Function Guidance System Considering AV Performance, Road Capacity and Environmental Factors

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Abstract: Autonomous driving (AD) functions are increasingly used on vehicle, but currently they might not perform better than human drivers. The adaptive cruise control (ACC) was selected as an example. Car following headway data of human drivers and ACC function were collected and analysed. The result shows that ACC function of most types of vehicles has larger headway than human drivers under the same travel speed. By modelling with random headway, decrease of road capacity with increasing share of vehicles using ACC were observed at some levels of travel speed. This article then promotes the concept of an AD function guidance system as a compensation to internet of vehicles yet under development. The system, installed on key road sections, gives drivers suggestions on the use of AD functions e.g. turning off ACC, to improve maximum road capacity and avoid congestions. Environmental, psychological, infrastructure and other key factors helping calibration of the AD function guidance system are proposed and analysed.

Keywords: Adaptive Cruise Control; Highway Information System; Road Capacity; Car Following

1. Introduction

In recent years, more and more new cars have been armed with advanced driving assistance system (ADAS), while basic autonomous driving (AD) functions such as adaptive cruise control (ACC) and automatic emergency braking (AEB) are increasingly involved in daily life. According to survey to manufacturers and government report, 38 companies conducted road tests for autonomous vehicles (AV) in Beijing in 2023. The total test mileage of AVs reached 38.93 million kilometers on various types of roads, including expressway, highway and city roads. However, the AD functions of current new cars perform more conservatively compared to experienced human drivers, which can cause a decrease in road capacity and additional travel time as they spread, despite allowing more drivers to be free of their steering wheels.

An AD function guidance system, in this article, refers to a system that relies on traffic and input of surrounding information. The system then gives suggestions on the use of their cars' AD function, mainly with large-scale overhead or roadside displayers.

Such information system has already been applied by highways around the world for the delivery of traffic jams, accidents, works and other information like travel time [1] [2]. With the development of V2X equipment and Level 4 vehicle platooning, roadside facilities can not only provide information but also control vehicles to drive without any interfere of human drivers (as a guide to machines) [3]. However, the large-scale application of V2X is still facing technical and economic challenges [4]. At the moment of transfer from human driven to AV, an upgraded guidance system facing human-AV co-pilot (L2 & L3 automation) would help accelerate this process.

In this article, AVs' influence on reduction of road capacity will be discussed. Therefore, the need for an AD function guidance system in key road sections could be explained. Taking other factors including daily traffic flow profile, weather conditions and drivers' tastes in to account, suggestions will be made for configuration and calibration of such a system under various circumstances.

2. Literature

Thausands of studies have been done on the capacity of a road section, from the very basic and handy model of the Highway Capacity

Manual (HCM) [5], to recent research on the highway on-ramp bottleneck [6]. In addition, there are multiple models and results over capacity of mixed traffic driven by human and AV [7] [8], some of them state that traffic flow would be smoother when there are more ACC-enabled vehicles.

Research on the efficiency of mixed human-AV traffic are based on calculation and simulation, while field tests for AV are mainly focused on basic driving safety, as seen in reports and protocols from authoritative institutions like Euro NCAP [9]. In China, automotive media are main cross-testers to new AVs [10], which mainly faced by the public and does not provide professional numerical conclusions.

There are rich but divergent answers to estimation for adoption of AVs. Salvini et al's research [11] suggests a legal framework to be improved to better contain AV, while Lukovics et al [12] say in their research that there is still a considerable number of regions not ready for AV. According to Wei et al [13] and Zhong et al's [14] research, people's opinions about freeing hands on the road vary according to their knowledge, trustworthiness to policy and technology, and even gender, which adds some uncertainty to mixed human-AV traffic.

3. Modelling Mixed Traffic and Capacity Reduction

Considering the limited available data input, in this article, a simple simulation method for different share and performance of AVs would be applied for the calculation of road capacity. The road capacity on each scenario could then be calculated.

3.1 Data Collection

3.1.1Human Car-following Performance

The human driving headway data was based on over 15000 pairs of leading vehicle (LV) and following vehicle (FV) steady car-following tracks collected from rooftop-view videos captured by cameras mounted on drones hovering above road sections as figure 1 shows. Tracks of moving passenger vehicles are first identified and debounced from all targets.

Pairs of LV and FV car-following tracks are then identified and classified through neural network algorithms, while acceleration and deceleration track pairs are removed. Then, they are further classified according to travel speed.

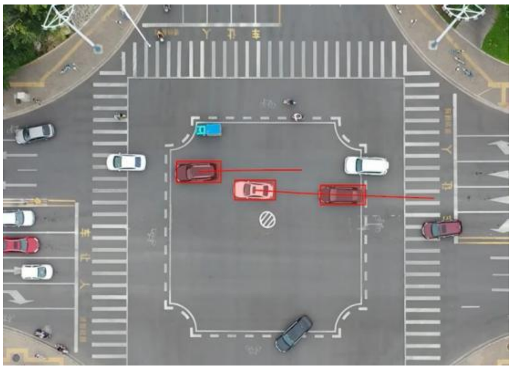

Figure 1. Identification of Vehicle Tracks from Rooftop-View

Figure 2 shows the distribution of human driving headway under different speed levels. The red parts of the bar include the vehicle with 5% shortest and 5% longest headway, the green part includes 70% headway around the median and the blue parts represent the 20% rest headway between extreme and median values.

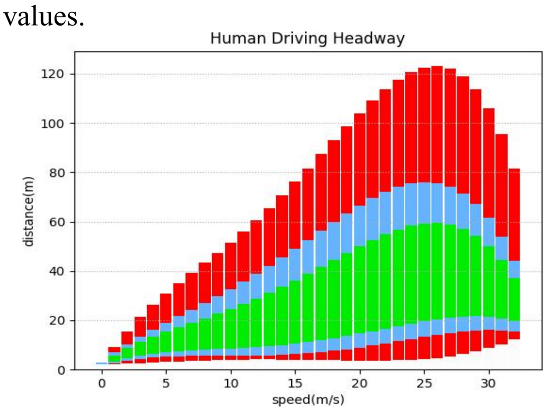

Figure 2. Collected Human Driving Headway of Steady Following

3.1.2ACC Car-following Performance

ACC driving headway were measured with GPS-inertial tracking equipment. The test was carried out in clear weather on dry, flat, long and straight freeway sections; the LV drives with the desired constant speed, while the FV drives with its ACC function enabled at indicated gear. The steady following headway would not be decided until the stable following status is reached.

Figure 3 shows part of distribution of ACC driving headway under different speed levels and ACC gears of some types of vehicles in series production. The human driving headway can be clearly seen that the ACC driving headway of most vehicles is longer than human drivers' in most situations. This result is quantified in section 3.

Figure 3. Driving Headway of Some Types of Vehicles' ACC Steady Following in the Following Sections

3.2 Modeling Data Generation

The modeling dataset is a randomly mixed group of numerical driving headway, which is sourced from two parts, namely human driving and ACC driving head- way. For each stage of travel speed, there will be one dataset. The selection of human driving headway follows distribution indicated in the previous section (5%-10%-70%-10%-5%). The ACC driving headway is very stable for each type and ACC gear of vehicles. The values are randomly chosen from the test values of all vehicles and their ACC gears as the ACC part of modeling dataset. Based on desired share of ACC-enabled vehicles, the two parts of the data were combined and mixed to form the car-following dataset for modeling. Figure 4 shows the formation of a dataset at 60km/h travel speed and 20% share of ACC-enabled vehicles.

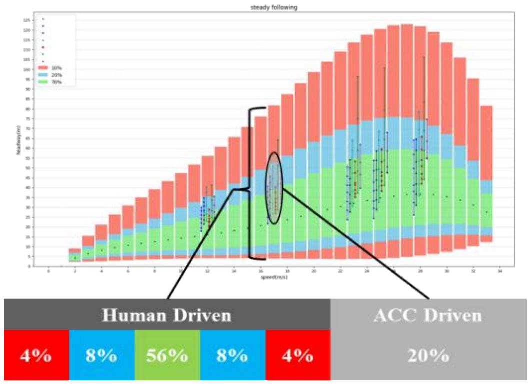

Figure 4. Composition of a Headway Modelling Dataset

3.3 Road Capacity Calculation

In this article, road capacity is defined as the number of vehicle front bumpers that passed a fixed point within one hour, with unit vehicle/hour. Distance between front bumper of LV and FV is represented by:

$D = d + L$

Where:

D =real driving headway for further calculation,

d = driving headway, chosen from driving headway dataset,

L= LV length, a random number following normal distribution with a mean of 5 meters.

By randomly choosing d values from the dataset, D could be generated one by one until the sum of generated D exceeds the 1 hour distance of indicated travel speed. Number of D has been added shows number of vehicle has passed the fixed point in one hour.

The following equation shows an example of road capacity calculation with 60km/h travel speed and 20% share of ACC-enabled vehicles:

$[D0 = (L0 + d1)] + [D1 = (L1 + d2)] + D2 + \ldots D1999 + D2000$

Assuming:

x=2000

$Dx = 60010m > 60000m = 60km/h * 1h$

x=0

The result road capacity is then 2001veh/h.

Table 1 and figure 5 shows road capacity for each combination of travel speed and share of ACC-enabled vehicles. For higher accuracy, the average value of 10 rounds of calculation was taken for each combination.

Table 1. Calculated Road Capacity under Each Combination of ACC Vehicle Share and Travel Speed

Share of AV/Speed	60km/h	70km/h	80km/h	90km/h	100km/h
0%	1897	1775	1740	1725	1680
5%	1872	1764	1740	1719	1686

10%	1848	1747	1723	1711	1703
15%	1821	1721	1698	1677	1693
20%	1799	1710	1688	1675	1692
30%	1740	1678	1692	1680	1695
40%	1712	1672	1677	1664	1694
50%	1701	1654	1659	1645	1699
60%	1680	1641	1653	1657	1686

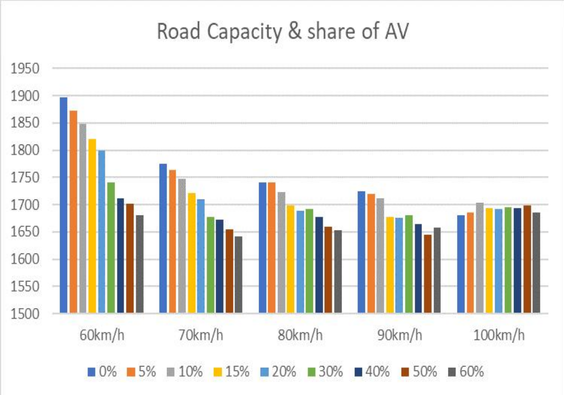

Figure 5. Calculated Road Capacity Shown with Bar Chart

Figure 6 shows the proportion of road capacity under each combi- nation of travel speed and share of ACC-enabled vehicles. The situation having 0% percent of ACC-enabled vehicles (100% human-driven) is set as a reference.

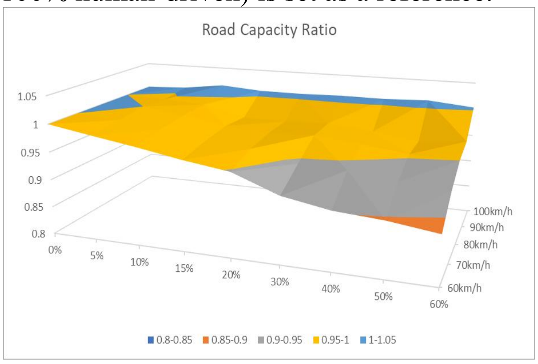

Figure 6. Calculated Road Capacity Ratio Shown with 3D Chart

3.4 Summary

The simulation result shows a clear reduction in road capacity with the increase in the share of ACC-enabled vehicles at 60km/h, 70km/h, and 80km/h. For the 90km/h and 100km/h situation, the share of ACC-enabled vehicles has negligible influence on road capacity. In this situation, the AD function guidance system can be set up on city expressway with a speed limit lower than 80km/h. When the key road section meets its saturate capacity at rush hours, the system recommends manual driving in order to increase the capacity of the road.

4. Key Factors of the AD Function Guidance System

Calculation in the previous chapter has proved a significant reduction of road capacity at an ideal highway under a different share of ACC-enabled vehicles and provided a simple operation logic of an AD function guidance system. To make real use of this result, in other words, to achieve acceptable traffic efficiency for most road users via an AD function guidance system, more surrounding environmental and psychological factors must be taken into account.

4.1 Environmental Factors

4.1.1Weather

Both human and ACC driving headway may change at complex weather conditions, e.g. at night without streetlight or rainy days, human drivers may choose to increase the gap. It is easy to use GPS & inertial navigators to perform tests for ACC functions in bad weather, but due to technical limitations the hover & video track collection method for car-following tracking may not work in low-beam and precipitation conditions. Human and ACC driving behaviour and road capacity in complex road conditions need to be further explored to ensure high efficiency for the AD function guidance system [15] [16].

4.1.2Road Profile

Curve and slope of roads may influence both human and ACC driving headway.

[17] [18] research has revealed human drivers' behaviour, similar research for ACC car-following is relatively less found [19]. The AD function guidance system is suggested to adjust key parameters according to the road profile to achieve a better fit.

4.1.3Flow-Time Profile

Traffic flow varies according to the time period of the day for a road section. Guiding information provided for peak hours, for example, recommend manual control, can increase drivers' burden at non-peak hours when the road section is clear enough for ACC function to take over. The threshold in which ACC becomes limit of road capacity shall be defined and calculated for each road section as reference to deploy the AD function guidance system.

4.1.4Long-term Factors

In a relatively short period for a couple of months or a few years, the share of ACC-enabled vehicles in a region may remain unchanged. When it comes to a period long enough for the passenger car fleet to renew and upgrade [20], ACC may gain a greater coverage and ensure a safe driving headway lower than human drivers. In addition, the share of non-passenger vehicles and total demand of a single road section may change according to road network and economy development. It should be emphasized that the database and key modeling factors of the AD function guidance system require regular renewal and verification.

4.2 Psychological Factors

The purpose of setting up the AD function guidance system is to advise drivers to use the AD (ACC) function wisely so that their own travel time and effort could be saved. Therefore, to serve road users, drivers' behaviour and the psychological factors behind it should be studied.

4.2.1Selection of ACC gears

Test result in section 2.1.2 shows good discrimination of driving headway over different ACC gears for all tested ACC-equipped vehicles. For some of the vehicle types, its range of ACC driving headway goes all the way up from the human driving median to the longest 5%. Such discrimination implies real driving headway and road capacity are decided not only by share of vehicles enable ACC, but also by which gear of ACC their drivers are using. Salioqi et al's research [21] shows a common increase in the headway of drivers using ACC. In real calibration process of the AD function guidance system, the ACC part of modeling dataset shall not be randomly chosen from possible vehicle types and ACC gears, but rather to conduct a study of local drivers' use of ACC function to acquire accurate data.

4.2.2ACC-aided VoT

Cost-benefit model (CBM) is frequently applied to transport projects. For eval- uation of time-saving efficiency, value of time (VoT) is the most used media to transfer time value to monetary value. VoT were seen as a fixed value in most applications. However, in a model that drivers can change their driving task (between manual drive and ACC control), their VoT might have undiscovered changes [22]. For example, Dai et al's research [23] has seen an increase in accept- able commuting time using AV: ACC driving might be more cost effective since they have more leisure with ACC enabled; In this situation, promotion of using ACC is the correct decision from CBM's point of view. This is to be deeper studied for a responsible output of the AD function guidance system.

4.2.3Rate of Guidance Following

It is inevitable that not all drivers would follow the system's guidance for all kind of reason such as (un)intentional ignore of information displayer or simply driving lazy despite VoT and risk. A calibration factor should be included during the generation of modeling dataset as well as tests to drivers on the adoption of information on roadside displayers in advance.

4.3 Calibrated AD Function Guidance Model

With all detailed real-world factors explained above taken into account, a full- scale flowchart of deploying an AD function guidance system can be drown as Figure 7 shows.

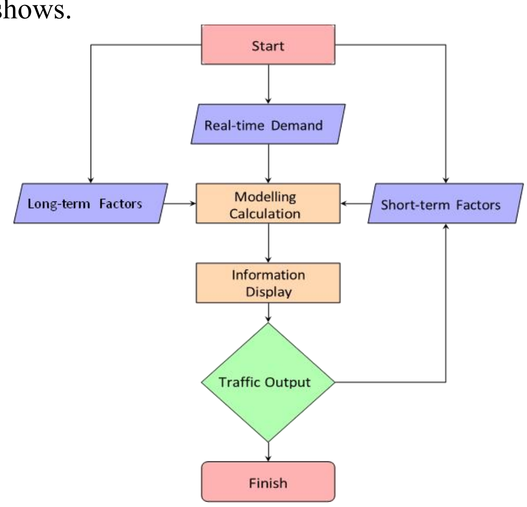

Figure 7. AD function Guidance System Working Flow Chart

In the flow chart, long-term factors refer to part of the environmental factors and user factors that would remain unchanged in a long period, i.e. road profile and VoT taste. Short-term factors refer to other factors that may change weekly i.e. weather, daylight, and real flow output.

5. Conclusion

By carrying out tests and comparisons, it is believed that current ACC-equipped vehicles are still to be improved to meet the same or even better efficiency as human drivers when it comes to driving headway. Different share of ACC- enabled vehicles, though making driving less stressful, may reduce maximum road capacity, which is critical on solving peak hour traffic congestion problem. This article suggests to introduce an AD function guidance system guiding drivers (not) to use their ACC function at specific times by providing related information via road side displayers, as a replacement of still growing V2X and internet of vehicles (IoV) infrastructure. The system is based on modeled capacity reduction caused by ACC implement; while incoming traffic demand exceeds maximum ACC-implemented capacity, the system will then suggest
drivers to quit ACC to reduce driving headway, thus increasing road capacity. Further beyond, this article proposes factors other than vehicle performance,
share, and travel speed. Environmental factors including weather, time, road profile, and long-term social development challenge the utility and robustness of the system. Psychological factors like ACC gear selection, VoT and guidance adaptability may influence accuracy and value of the system. These factors over usage and performance of ACC and other related AD functions have yet to be further studied to make the AD function guidance system and any other subject helping road traffic to transfer from human to autonomous driven smoothly to perform better.

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