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Analysis of the Impact of Autonomous Driving on Road Design and Traffic Control

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Abstract: As a key breakthrough to promote the reform of the transportation industry, autonomous driving technology is leading the profound change of road design and traffic control mode. This paper starts with an overview of autonomous driving technology, analyzes the specific impact of this technology on road design and traffic control, and discusses how autonomous driving technology promotes the optimization of road design adaptability, intelligent upgrade of traffic signal control system, traffic flow management and safety improvement. At the same time, this paper discusses how autonomous driving technology drives the future development of road design and traffic control, and promotes innovation in traffic control strategies and the integration of multi-level traffic systems. The research results provide theoretical support for the progress of intelligent transportation system and the wide application of autonomous driving technology.

Keywords: automatic driving; road design; traffic control; intelligent transportation

1. Introduction

In the context of the rapid development of autonomous driving technology, the transportation field is encountering unprecedented opportunities and challenges. Traditional road design and traffic control models are difficult to adapt to the new requirements of autonomous vehicles, so it is imperative to promote innovation and improvement in related industries. The application of autonomous vehicles not only changes the traditional driving habits, but also requires the corresponding adjustment and optimization of road design and traffic control system. The objective of this paper is to deeply analyze the impact of autonomous driving technology on road design and traffic control, and explore its promoting role, in order to provide theoretical basis and practical guidance for the construction of future intelligent transportation system.

2. An Overview of Autonomous Driving Technology

Autonomous Driving Technology refers to the integration of sensors, artificial intelligence algorithms, on-board data processing systems, and vehicle-to-vehicle communication (V2V), enabling the vehicle to independently perceive the environment, make decisions, and operate without human intervention. According to the level of technological development of autonomous driving, there are usually five levels in the world, from L0 (full manual control) to L5 (fully automatic navigation). Between L0 and L4, the degree of automatic control of the vehicle gradually increases, involving partial to full automation of the driving task, while level L5 represents full autonomous driving, where the vehicle is able to drive itself under any conditions and no longer relies on a human driver [1]. The

core components of autonomous driving technology include environment awareness (using various sensors such as radar, lidar, cameras, etc., to gather information about the surrounding area in real time), decision planning (analyzing and evaluating this information through deep learning and artificial intelligence technologies), and executive control (accelerating, braking, and steering the vehicle according to the decision output). With the continuous development of technology, automatic driving is gradually moving from the experimental period to commercial application, and it is expected to be widely used in many fields such as public transportation, freight and private cars in the future [2].

3. The Impact of Autonomous Driving on Road Design and Traffic Control

3.1. Adaptive Changes in Road Design

The development of autonomous vehicles has prompted road layouts to be adjusted to match their precise handling performance. Compared with conventional vehicles, autonomous vehicles can maintain shorter distances and more constant speeds, which greatly improves the efficiency of road resources. For example, the width of lanes and the distance between vehicles can be reduced in an autonomous driving environment. Assuming that the lane width is set according to traditional design criteria, and that the lane width requirement for autonomous vehicles is different, the change in lane width can be expressed by the following formula:

$$\Delta W = W_0 - W_1 \quad (1)$$

Through the application of autonomous driving technology, the distance between vehicles can be effectively shortened, allowing more vehicles to be accommodated on the road under the same road width, thus significantly improving road capacity. During busy traffic hours, autonomous vehicles can use existing roads in a more efficient way, especially in urban road conditions, autonomous vehicles can maintain a high traffic capacity within a limited road range, effectively alleviating the problem of traffic congestion. At the same time, the design of the intersection will also be optimized. Traditional intersection designs rely on traffic signals or human commands to manage the flow of traffic, but autonomous vehicles can intelligently work together to self-optimize their path based on real-time traffic conditions. This allows the design of intersections to become intelligent, effectively reducing traffic congestion and enabling precise collaboration between vehicles. In the future, intersections may be able to move away from reliance on traditional signal lights and instead achieve more efficient passage through vehicle networks and intelligent traffic control systems [3].

3.2. Intelligent Upgrade of Traffic Signal Control System

Autonomous driving technology has played an important role in changing the traditional traffic signal control system. Compared with the old signal light system, the latter operates according to a preset schedule and cannot be dynamically adjusted according to the real-time traffic flow, which is prone to traffic congestion and inefficient use of the signal light [4]. Autonomous vehicles can use vehicle-to-vehicle communication technology (V2V) and vehicle-to-road communication (V2I) capabilities to transmit data in real time to the traffic signal control system, and then intelligently adjust the signal light control scheme, thereby improving traffic mobility. Assuming that the traffic flow at a certain time is F_{floe}, and the adjustment period of the signal light is T_{adjust}, the period of the signal light can be dynamically adjusted based on the traffic flow, and the formula is as follows:

$$T_{adjust} = f(F_{flow}) \quad (2)$$

Where $f(F_{flow})$ is the function between traffic flow and signal period, reflecting that the adjustment period of traffic lights will be adjusted according to the change of traffic flow. For example, when the traffic flow of a certain section is high, the green time of the traffic signal will be automatically increased to allow more vehicles to pass smoothly. In the case of low traffic flow, the green time of the signal will be reduced to minimize vehicle

waiting time. This kind of intelligent control not only improves the traffic efficiency of the road, but also helps to reduce the traffic congestion phenomenon and realize the reasonable allocation of traffic resources. With the wide application of autonomous vehicles, traditional traffic signal control systems will gradually be replaced by new systems based on real-time data and artificial intelligence technology, which will greatly improve the flexibility and efficiency of traffic management. In addition, the intelligent signal control system can also predict traffic demand through data analysis, and make pre-adjustment accordingly, so as to effectively prevent traffic congestion caused by sudden increases in traffic [5].

3.3. The Impact of Autonomous Driving on Traffic Flow and Road Capacity

With the widespread application of autonomous vehicles, road efficiency and road capacity will be significantly enhanced. Unlike traditional traffic, which is limited by the reaction speed and driving habits of human drivers, autonomous vehicles rely on high-precision sensing equipment and real-time decision support systems to achieve the shortening of vehicle spacing and the balance of speed, which not only reduces the gap in traffic, but also greatly improves the road capacity. Assuming that the traffic flow is Q, the speed is V, and the distance between vehicles is d. Then the relationship between traffic flow and vehicle distance can be expressed by the following formula:

$$Q = \frac{V}{d} \tag{3}$$

Where, V is the average speed of vehicles, d is the average distance between vehicles. Autonomous vehicles can reduce the gap between vehicles through high-precision control systems, thereby increasing traffic flow at the same road width. Compared to manually driven vehicles, autonomous vehicles can control speed and following distance more precisely, ensuring safety while optimizing the utilization of road resources. Because autonomous vehicles can achieve vehicle-to-vehicle collaboration, especially in multi-lane environments such as highways, they can reduce traffic congestion through platoon collaboration and increase the overall traffic volume on the road. In this case, the increase in traffic flow is not only due to the reduction of the spacing between vehicles, but also because the autonomous vehicles can coordinate the speed of the vehicle, reducing the sudden braking and frequent lane changes that are common in human drivers, thus ensuring the smooth flow of traffic [6].

3.4. Traffic Safety and the Possibility of Reducing Accidents

Autonomous driving technology can significantly improve traffic safety and effectively reduce the frequency of traffic accidents. In conventional driving mode, human factors such as driver's negligence, fatigue and inattention are often the main causes of traffic accidents, while autonomous vehicles can avoid these human risks through accurate perception systems and fast decision-making algorithms, and greatly reduce the probability of traffic accidents. Assuming that the probability of traffic accidents is $P_{acciden}$, and the probability of accidents under traditional driving is $P_{accident0}$, then the change of accident probability after the introduction of automatic driving technology $\Delta P_{accident}$ it can be expressed by the following formula:

$$\Delta P_{accident} = P_{accident0} - P_{accident} \tag{4}$$

Through real-time monitoring of the surrounding environment, the autonomous driving system can quickly perform braking, steering, and other operations when it identifies hidden risks, thereby avoiding collisions. This reaction speed is far faster than that of human drivers, especially in emergencies, autonomous vehicles can respond quickly, compared with traditional drivers may cause accidents due to slow response or poor judgment. Autonomous vehicles can also share real-time traffic information through vehicle-to-vehicle communication technology (V2V), reducing the risk of collisions caused by information asymmetries or blind areas of vision. The vehicle can sense the danger ahead in advance and adjust the driving route, effectively preventing accidents such as rear-end

collisions. In addition, the introduction of automatic driving technology can also avoid unnecessary dangerous driving behaviors such as sudden braking and rapid acceleration through algorithm optimization, so as to further reduce the probability of traffic accidents [7].

4. The Role of Autonomous Driving in Road Design and Traffic Control

4.1. Promote the Development of More Efficient and Intelligent Road Design

The introduction of autonomous driving technology has directly contributed to the development of road design in a more efficient and intelligent direction. The traditional road design is mostly based on the operating habits and reaction ability of human drivers, which leads to the underutilization of many road resources. With the development of autonomous driving technology, vehicles achieve precise control and intelligent collaboration, which makes road design can become more flexible, lane width, traffic signs, intersection design, etc., can be adjusted according to the performance of autonomous vehicles. Autonomous vehicles can drive stably in shorter vehicle distances and narrower lanes, effectively reducing traffic gaps, so lane width and vehicle spacing can be appropriately reduced, thereby improving road transportation efficiency. For example, on highways, autonomous vehicles can use vehicle-to-vehicle communication systems (V2V) to reduce the distance between vehicles, so that more cars can be accommodated in the same lane and improve the road capacity. In addition, autonomous vehicles can also collaborate with intelligent transportation infrastructure through vehicle-infrastructure communication systems (V2I) to achieve real-time adjustments such as traffic signals and speed limit signs, which greatly improves the flexibility of road design. In terms of intersection design, autonomous vehicles can coordinate adjustments based on real-time traffic information, and may even achieve smart intersections without traffic lights, reducing traffic congestion and improving road utilization. Through these intelligent designs, autonomous driving technology not only promotes the rational use of road resources, but also effectively alleviates the traffic pressure on urban roads. With the further popularization of autonomous driving technology in the future, intelligent road design will lay a solid foundation for building a more efficient and sustainable transportation system. The potential impact of autonomous driving technology on various road design parameters, including lane width, intersection design, and road capacity, is shown in Table 1.

Table 1. Impacts of Automated Driving on Road Design.

Design parameter	Traditional road design standards	Impact of autonomous driving technology	Improvement range
Lane Width (m)	3.5	3.0	0.5m less
Lane spacing (m)	2.0	1.5	0.5m less
Intersection design (individual)	5	3	Reduce by 2
Road capacity (vehicles per hour)	1800	2500	Add 700 units

As shown in Table 1, autonomous driving technology enables road design to reduce lane width and lane spacing, optimize the number of intersections and road capacity, and improve the overall capacity of the road while ensuring safety.

4.2. Promote the Innovation and Development of Traffic Control Strategies

The application of autonomous driving technology has not only changed the design concept of road layout, but also promoted the innovation of traffic control strategies. Traditional traffic control strategies are usually based on preset schedules and mechanical control of signal lights, which cannot respond to changes in traffic flow in real time, often resulting in poor traffic flow and congestion. The introduction of autonomous driving

technology makes the traffic signal control system more intelligent and flexible, and can dynamically adjust according to real-time traffic flow, speed and road condition information. Through the real-time data exchange between the vehicle and the traffic infrastructure, the signal light can adapt to the change of the traffic flow, so as to ensure the smooth and efficient traffic flow. Cooperation among autonomous vehicles enables them to maintain more accurate speeds and distances between each other, and optimizes and smooths traffic flow through vehicle-to-vehicle communication (V2V) and vehicle-to-infrastructure communication (V2I), thereby reducing traffic accidents and congestion. Especially during peak hours or in sections with large traffic flow, autonomous driving technology can dynamically adjust speed and flow, effectively reduce traffic pressure and improve road capacity. In addition, the introduction of autonomous driving technology makes the traffic control strategy no longer rely solely on the periodic control of signal lights, but comprehensively improve the efficiency of traffic flow management, optimize traffic scheduling, and improve the operating efficiency of the overall road network system through the cooperation and data sharing between vehicles. With the continuous progress of intelligent transportation systems, the close cooperation between autonomous vehicles and transportation facilities will make traffic control strategies more flexible and real-time, thus laying a solid foundation for the construction of intelligent urban transportation systems. The innovative impact of autonomous driving technology on traffic control strategies, including signal light cycle, traffic flow optimization, and control response time, is shown in Table 2.

Table 2. The Innovative Impact of Autonomous Driving on Traffic Control Strategies.

Control index	Traditional traffic control standards	Optimization of autonomous driving technology	Improvement range
Signal lamp cycle (seconds)	60	45	15 seconds less
Traffic flow optimization (%)	70%	90%	Increase by 20%
Control response time (seconds)	15	5	10 seconds less
Network congestion index (%)	40%	20%	20% reduction

As shown in Table 2, autonomous driving technology optimizes traffic signal cycles, reduces response times, and significantly improves the efficiency of traffic flow management, thereby reducing the congestion index of the road network and optimizing traffic control strategies.

4.3. Promote the Integration and Collaboration of Multi-Level Transportation Systems

The introduction of autonomous driving technology not only changes the design of individual roadways but also promotes the integration and collaborative development of multi-level transportation systems. The modern urban transportation system includes expressway, urban road, rail transit, public transportation and other diversified modes of travel. Traditional modes of transportation often isolate these systems, but autonomous driving technology through the Internet of vehicles (V2X) effectively realizes the connection and collaboration between different modes of transportation, thereby improving the efficiency of the entire transportation system. For example, autonomous buses and taxis can seamlessly interface with rail transit systems or traditional bus systems, creating a more efficient public transport network. Passengers can intelligently arrange or request autonomous vehicles according to their own needs and real-time traffic conditions, effectively solving the "last kilometer" problem of travel. Autonomous driving technology can also improve the coordination between different modes of transportation, shorten waiting

times, optimize route selection, and thus reduce the pressure of traffic congestion. By dynamically adjusting routes and avoiding rush hour congestion, autonomous vehicles can significantly improve travel efficiency. In addition, on the basis of whole-process cooperation and information sharing, autonomous vehicles can also reduce traffic accidents caused by human driving errors and improve road safety. With the widespread deployment of the technology, systems at different levels in the transportation network will achieve closer integration, forming a smart, connected transportation ecosystem. This integration not only improves traffic efficiency but also enhances overall transportation safety. In the future, the synergy of autonomous driving, shared mobility and public transportation will make urban transportation more efficient, flexible and environmentally friendly, promoting green mobility and sustainable transportation development.

5. Conclusion

The rapid development of autonomous driving technology is gradually changing the design and management mode of traditional transportation systems. By optimizing road design and improving the intelligent level of traffic control, automatic driving not only effectively improves the road capacity, but also greatly reduces the occurrence of traffic accidents, thus promoting the safety and sustainable development of the traffic system. At the same time, autonomous driving technology also promotes the integration of multi-level transportation systems, providing new solutions for the efficient operation of urban transportation. With the further maturity of the technology, autonomous driving will achieve a deeper integration with intelligent transportation infrastructure, creating a more environmentally friendly and intelligent transportation ecosystem, and bringing far-reaching impacts on social and economic development as well as on people's mobility patterns.

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