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# The Coordinated Development of Digital and Intelligent Transportation Infrastructure with Autonomous Driving Technologies

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**Abstract:** With the approach to mass commercial application in the future, this paper discusses the coordinated development logic and routes between the intelligent transportation system and intelligent driving. Analyzes the limits of individual vehicle intelligence and makes a case for the need to coordinate vehicles with roads, and clarifies how roadside infrastructure may supplement the limitations in on-board sensing technologies; presents a "layered empowerment and progressive deployment" strategy, and discusses related issues; and finally provides some policy and industry recommendations for informing future smart transportation system development.

**Keywords:** Digital and intelligent transformation of transportation infrastructure; Vehicle-to-everything (V2X); Edge computing

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## 1. Introduction

The evolution of self-driving technology is now entering the "deep water zone." Take high-level automated driving (Level 4 and up) as an example: it faces insurmountable long tail problems and extreme cases on complicated city street scenes, which cannot be fully or safely solved by today's techniques. Meanwhile, the mainstream pure vision perception solution and the vehicle-intelligent technology approach are expensive and have a low degree of credibility, limiting industry growth at scale.

China is driving the convergence of "New Infrastructure" and "Transportation Powerhouse," calling for accelerating the development of new infrastructure, including intelligent transportation systems, and offering policy and financial incentives to upgrade roadside facilities. Transportation agencies and companies nationwide are using this opportunity for technology innovation and deployment, to achieve an efficient, safe, and green development of the transport system; (from the perspective of transportation management in general) optimizing system performance, a fundamental need and goal of transportation planning; We have to create an effective link and collaboration between the road and vehicle in order to improve its safety, efficiency, and environmental sustainability of the transportation system via, for example, vehicle-road coordination, thereby building an intelligent, effective, and environmentally sound new generation of transportation infrastructure [1].

## 2. State-of-the-art

Autonomous driving is still facing some bottlenecks that need to be solved urgently. First, from the aspect of environment perception, due to the sensor's physical limitations, vehicles find it difficult to obtain information from blind spots, which poses a challenge to complete identification of potential risks in urban areas; Second, under bad weather conditions, the visual sensor, lidar, and mmWave radar are impaired, which affects the environment perception and judgment of this system. Third, under high-dynamic and uncertainty driving environments, the single intelligent vehicle system can hardly precisely capture others' intentions of behavior and lacks effective online decision-making ability. Smart Infrastructures for Intelligent Transportation System (ITS) is moving away from the conventional ITS towards digitized, connected, and intelligent, which focuses on close cooperation with city digital twin systems for the purpose of optimizing the traffic resource distribution and improving the overall performance of the system in real-time [2].

Vehicle-to-Everything (V2X): V2X has been developed rapidly in recent years, which can support more and more complicated use cases. Vehicles and the roadside infrastructure are able to communicate with each other at a speed of milliseconds for exchanging messages and sharing information using high-speed wireless communications technology, thus extending the capability of individual vehicle intelligence, improving driving safety, traffic efficiency, and overall system intelligence.

## 3. The core enabling force behind the digital and intelligent transformation of transportation infrastructure

(1) Digital Basis

The digital basis of digital intelligent transformation of transportation facilities includes building a large-scale holographic perception system of transportation objects and constructing high-precision time-space reference systems. Various heterogeneous sensing devices are deployed on the core road area, collecting massive multimodal data in a timely manner; After processing and analysis, this data offers a detailed characterization of the transportation elements which are "visible, measurable, and knowable". This fine-grained spatio-temporal reference allows for an integrated, high-resolution position reference and timing. The establishment of reference stations and the use of a multisource fusion positioning technique offer high-precision positioning and timing service to roadside units. High precision space origin ensures the accurate alignment of perception information, while the time stamp ensures homogeneous timestamps of all data, which is a prerequisite to both vehicle-road communication and synchronization, and serves as a foundation of future intelligent vehicle-road cooperation [3].

(2) Communication Interconnection

Build a vehicular infrastructure cooperative communication network based on the C-V2X communications network. Evolved from cellular communication, C-V2X can provide full-duplex communications with high reliability and low latency. Direct communication of C-V2X supports applications like emergency brake warnings, while support for cellular network connectivity enables high-throughput data exchange applications. Network infrastructure: Network lays the cornerstone of mass-scale C-V2X deployments, and 5.5G can fulfill the demand for automated driving and V2I cooperation in future years. With the massive deployment of RSUs working together with core networks and edge clouds, an integrated "vehicle-infrastructure-cloud" communication network is provided for reliable communications support.

(3) Intelligent Engine

The intelligent engine is made up of roadside edge computing (MEC) and centralized cloud, equipped with collaborative perception & decision-making algorithm, in order to form a closely connected computing ecosystem. Real-time perception information is processed at the roadside edge computing node, while the central cloud platform handles world coordination and smart optimization. The collaborative perception and decision-making algorithm is the “brain”, and the collaboration of roadside edge computing and center cloud endows the transport network with intelligence.

(4) Service-Oriented Service

It provides different service tiers, including information alert (I1), to collaboration control (I5) for various levels of AVs. At the information alert (I1) level, digital and smart infrastructure provides the vehicle/driver with up-to-date information about the road environment, as well as alerts for traffic events. The roadside perception system transmits its detections over C-V2X communications, complementing on-board sensors for safer driving. At automated driving assistant levels (I2–I3), the infrastructure provides more actionable information for decision-making in order to assist with vehicle strategies and changes. In automated (I4) or full automation (I5) cooperative control, roadside edge servers or local clouds cooperate with vehicles for decision-making and motion planning, ensuring traffic safety. With the hierarchical service framework, intelligent transport facilities can be customized for various kinds of automated vehicles, developing a smart transportation system that can improve road traffic performance, reduce the rate of accidents, and enhance the traveling experience [4].

# 4. Pathways and scenarios for collaborative development

## 4.1. Technical Path: A progressive evolution from “information interaction” to “perception sharing” and ultimately to “control collaboration”

During “Information Interaction”, there is a rudimentary level of information interoperability between V2I and V2V: roadside units broadcast traffic signal times to vehicles, where vehicles broadcast their status or driving intention to solve the “information asymmetry” problem. It is the basic cooperative level, relying on communication technology such as C-V2X. In the “Perception and Sharing” stage, when technology matures, and more infrastructures are equipped with environment perception capabilities, the perceived information will be shared and integrated. The data sensed by roadside sensors will be processed at edge computing nodes and sent back to the vehicle through C-V2X links. Vehicles integrate the roadside sensing and their own sensing together into a “map of the environment”, which helps make decisions in autonomous driving more reliable, for instance, roadside radar sensing of oncoming cars in a curve for collision avoidance. The higher level “Control Collaboration” stage, transportation infrastructure closely participates in the vehicle dynamic decision-making and motion control to achieve “vehicle-road-cloud” integrated collaboration control. Edge computing nodes on the roadside, as well as clouds, should have strong abilities to make real-time decisions and global optimizations. For example, allocating the sequence of flows and suggested speeds at complicated junctions, where the cooperation between controls is based on very advanced and fully integrated technologies in order to provide a globally optimal (and coherent) behavior of the whole transportation system [5].

## 4.2. Implementation roadmap

Ensure that implementation follows a logical progression in terms of complexity and scope, including moving from pilot programs or small-scale implementations to larger-scale implementations, and moving incrementally forward. This ensures the technical solutions are feasible, cost-effective, and safe, and it accumulates experience gradually in order to enable the scale of implementation. Firstly, the priority is given to closed or half-open environments like highways, urban expressways, ports, and industrial parks—these scenarios have consistent traffic flows and low interference, enabling implementation of smart, digital infrastructure and delivering substantial operational efficiencies. For example, highways can improve traffic efficiency and safety; ports and industrial parks allow for more fine-grained scheduling. After finishing pilot verification in a close/semi-close environment, the method should be expanded for complex urban roads requiring a better perception capability. Pilot projects must initially be on arterials and key intersections, but later can expand to minor and collector streets as the system is proven, eventually forming a full-coverage network. Implementation is based on the “pilot-promote-adopt” roadmap: “Pilot” refers to small-scale validation within representative scenarios for standard refinement; "Promote" means scaling up after successful trial in order to optimize technologies/models; "Adopt" implies widespread deployment when the technology becomes mature, making it the norm, not the exception. It will reduce risk and deliver steady, effective delivery of digital and smart infrastructure development [6].

## 4.3. Typical scenario analysis

### 4.3.1. Security features: Collision prevention at intersections, early warning for vulnerable road users, and enhanced weather awareness

Intersection collision avoidance is one of the most typical use cases for V2I communication, which can be applied to safety applications. The existing traffic accidents at intersections are mostly caused by occlusion: driver mistakes, or aggressive lane changes. Smart & Connected Infrastructure utilizes a number of sensors at intersections for detecting the current status of traffic entities. The roadside edge computing node processes the collected information in real time, identifies possible collisions, and warns vehicles through C-V2X communications. In the case of AVs, the alarm prompts escape actions; for human driving, the on-board terminal alarms by visual/audio signals. The early alert and active intervention shorten reaction time and decrease accidents [7].

Early Warning System for VRU, which is an early warning system protects vulnerable road users like pedestrians, bicyclists, etc. In conventional traffic environments, missed pedestrian/cyclist accidents occur often. Digital and smart infrastructure deployed with dedicated sensors accurately detects the state of pedestrians/cyclists. The system provides warnings for vehicles and alerts pedestrians by activating road warning lights when it detects the entry of a vehicle into a dangerous area or a conflict between vehicles. For example, a roadside system can give the vehicle a warning before it is too late if the pedestrian crosses a zebra crossing, where no traffic light is present; nighttime recognition can be facilitated by technologies such as an infrared camera, timely and accurate warning;

The augmented severe weather perception scenario solves the problems that on-board sensors suffer from, such as performance degradation and poor sensing ability under bad weather conditions. Heavy rain and thick fog affect the performance of the sensor and shorten the driver's line-of-sight distance. The digitalized and intelligent infrastructure installs all-weather roadside sensors and weather monitoring instruments to acquire real-time weather information and road surface condition information, and provides them to vehicles. When facing thick fog in front of it, the roadside system warns the vehicle about fog existence, suggests proper spacing for safe driving, and supplies accurate environment perception information that can be used for making decisions, thus guaranteeing driving safety.

### 4.3.2. Efficiency categories: Green wave passage, coordinated scheduling in congested areas, and merging control of highway ramps

The green wave traffic method can effectively improve the utilization of urban roads. Conventional traffic lights are usually unable to achieve optimization in local area road networks. Digitalization and intelligence construction install related equipment on the main trunk line and link it up with regional traffic cloud centers, supporting the collection of real-time traffic data. Using both real-time and historical data, the cloud server can optimize signal timing for main intersections, establishing "green wave corridors." Recommended speeds for vehicles allow them to experience continuous green lights that reduce their stop-and-wait times and improve traffic flow (For example, optimize signal timing along a major artery in the morning rush hour). Green wave speed recommendation is provided by the roadside system to further improve its performance [8].

Congested Area Collaborative Scheduling Scenario. The congested area collaborative scheduling scenario is aimed at alleviating local city traffic congestion, which can monitor the real-time situation of traffic flow in congested areas and their surroundings through digital and intelligent facilities, then analyze the cause and assessment range based on the combination of historical and current data, and formulate coordination strategies with the help of the cloud-based control platform. On one side, it provides warning messages and diversion suggestions for dispersing traffic flows; on the other side, it manages incoming vehicle streams and adjusts signal timings in real-time for expediting congestion mitigation. For example, the system informs and shifts travel times in response to traffic buildup around business areas.

Highway ramp merging control has always been one of the most important scenarios in terms of improving traffic efficiency, as well as decreasing accident rates. Under conventional systems, vehicles on the main road and ramps frequently suffer from different speeds. The digital and intelligent infrastructures deployed in highway corridors or ramps can accurately monitor the status of vehicles and their intention to merge. Algorithms at the roadside edge computing node produce guidance commands for both main road and ramp vehicles. The proposed framework can achieve more intelligent vehicle-road cooperative driving through direct coordinated control so as to ensure a safe merge process with no accidents occurring during the entry of the ramp by each connected vehicle [9].

### 4.3.3. Service category: Includes automatic parking guidance, bus priority, and support for special vehicles

Guidance of automatic parking: suitable for large parking lots, etc. Roadside system uses equipment to scan the information about parking spaces, offering parking guidance for drivers. Procedure: After entering the parking lot, the roadside system provides drivers with free-space information as well as the best parking route through V2X communications. In the parking process, the system detects the car, follows it, and guides it; the driver just has to follow the instructions. In the case of a vehicle having an automatic parking function, the roadside unit complements the sensor limitation on board, increasing the parking success rate and safety.

Public transit priority case: Applying smart technology in order to make buses faster, more attractive, and efficient to ride, while promoting green travel. The sensors and other devices are placed on the bus routes as well as at the stops in order to track bus information and road conditions. As the buses get closer to an intersection, the roadside transmits information to a signal controller that changes the phase of the traffic signals in order to give priority to the transit vehicle. The platform will inform the driver of alerts and possible routes; it will provide a passenger with an estimated time of arrival (ETA) to their destination. The frequency of departures as well as schedules can be changed depending on the number of riders.

Special Vehicles Priority: In this case, we consider that the focus of the system is the special vehicle's priority passage. Digital and intelligent infrastructure would work together with traffic control centers in order to collect data regarding vehicles, while roadside systems observe traffic status. By means of V2X communications, the system notifies other cars by avoidance instruction and also dynamically controls traffic lights in order to allow the special vehicle a priority pass. Information variable signage provides traffic control instructions for detouring and thus reduces the response time [10].

## 5. Key challenges

Technical standard issues: Heterogeneous standards of the vehicle-road-cloud interface, data format, communication protocol, and security authentication, as well as the different format requirements among companies and organizations, prevent the sharing of information between RSUs and OBU's. This hampers the integration of systems and raises costs, inhibits interregional and interplatform cooperation, presents a risk to security, and limits the use of digital, smart technology generally.

Security and Privacy Issues: Transportation digitalization is based on data interoperability, while a large amount of data is generated with sensitive information and personal privacy, exposing the critical asset for interception or tampering during transmission, vulnerable with respect to safe storage, and with unclear use boundaries. We must protect people's privacy with respect to information about them; otherwise, we will not achieve broad acceptance for coordinating vehicles and roads.

Difficulties in technology integration, system compatibility: It is challenging to combine the existing conventional facilities with new digital-intelligent ones, as technologies do not match each other. Much of China's legacy transport infrastructure does not support the digital-intelligent needs, posing technical challenges to upgrading. Varying interfaces and protocols are required for facilities built during different periods due to the enormous amount of adaptation work. Digital-intelligent systems involve the integration of various cutting-edge technologies; stable and efficient system coordination is still challenging to achieve. Data integration and data cleansing play an important role in the accuracy of algorithms.

Legal, Regulatory, and Ethical Issues: Existing law and regulation cannot easily accommodate a world of connected and automated vehicles, with major ethics questions. Vehicle-road coordination technology challenges existing traffic laws and regulations regarding, for example, liability and insurance claims, while the question of who owns what data needs to be regulated. Vehicle-Road Coordination Systems should agree on ethical guidelines in case of a moral dilemma, which will have to go through the public discussion process, especially with regard to the issue of access (the "digital divide") and human rights concerns.

## 6. Future perspective

To promote the coordination of departments, we will build an inter-departmental joint conference system to break down the walls between them and make policies with synergy. We will cultivate talents and do technical R&D by setting up related majors at colleges and universities, increasing R&D, and developing independent technology capability. The infrastructure should be upgraded through proper management and appropriate investments for adequate equipment. In the near future (within a time frame of 5-10 years), we envision that VRCs can be widely deployed for commercial applications to achieve safer operations of autonomous vehicles under certain conditions with much better traffic performance and safety levels.

## 7. Conclusion

Digitalization and Intelligence Transformation of Transportation Infrastructure is an essential enabling technology to build "collective intelligence" for Autonomous Driving & Future Transportation, which requires following the "vehicle-road coordination" development philosophy. Only by integrating perception, decision-making, and control coordination deeply together would vehicles transcend the limitations of stand-alone intelligence, consistently prioritize transportation safety and congestion issues, and create new industries and business models. These collaborative efforts are difficult to develop, requiring technological advances and convergence of technology, industry, policy, and regulation to occur simultaneously.

## Disclosure statement

The author declares no conflict of interest.

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