Research and Application on Design of Underground Container Logistics System Based on Autonomous Container Truck

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Abstract. In this paper, a kind of underground passage automated freight transport system based on the autonomous dual-mode container truck is proposed, and the overall structure of the automated freight transport system, the allocation of the transportation equipment, the comprehensive design of underground passage, the comprehensive analysis of transportation organization, the reasonable layout of the freight transport terminal, and the design of connection with the overall operation of the port are studied. Taking the connection passage between the central operation area and the eastern operation area of Yantian Port under planning and construction as an example, this paper expounds the application of the underground automatic freight transport system design method in the underground container logistics system within the port area. Based on the current situation and the long-term planning requirements of Yantian Port, the overall route of the connection passage between the central operation area and the eastern operation area is studied; the dual mode transportation organization model based on the combination of autonomous driving and manned driving is designed, and the manned driving mode shall be adopted within the operation area. In the connecting tunnel, there is the interference-free, fully-enclosed, line-fixed, and no man’s land application scenario, and the autonomous driving mode shall be adopted. The corresponding ground switching area is proposed to match the dual-mode transportation system of the autonomous dual-mode truck; such switching area is composed of the mode switching area, truck storage area, and driver rest and management room. Compared with the traditional tunnels, the autonomous freight transport passage has obvious advantages in saving project cost and improving transport efficiency.

1. Introduction
The increasing demand for the development of the urban freight transport is accompanied by some inevitable problems. The development of e-commerce leads to the rapid development of courier business; however the traditional delivery mode is faced with the problems such as low delivery efficiency, poor quality of delivery service, and social impact. With regard to the port cities, most of the large-sized container ports are built on the basis of cities, resulting in the highly overlapping with the urban areas, and the collection and distribution land transport from the ports needs to pass through or occupy a great number of the urban road resources; the unreasonable collection and distribution mode at the port, the high proportion of road transportation, and the contradiction between cities and
ports is prominent, the freight transportation mainly in reliance on the ground container trucks brings a series of problems, such as traffic congestion, traffic safety and environmental pollution, so that the comprehensive environment of the port cities is deteriorating [1]. In addition, the urban freight transport will also face the problems such as the shortage of labor and the high freight cost arising from the labor costs. The sustainable new freight transport methods are required to solve the negative problems caused by the urban freight transport.

Due to the gradual improvement and maturity of the theoretical system of underground logistics planning, in particular the development and application of the technologies such as automated control and unmanned driving, the underground logistics freight transport system has become one of the planning and design schemes mainly considered in the comprehensive freight transport system in the cities, port areas or logistics parks [2-5]. At present, the technology of autonomous driving realized on the expressway, special road and other relatively closed environments is relatively mature; however, due to the limitations of the technology, there are the technical obstacles to the autonomous driving technology on the narrow and crowded urban roads with much interference as well as in the industrial parks or ports with complex loading and unloading industry, it will take a long time to make the technical breakthrough [5-8]. Therefore, it is not feasible to realize point-to-point transport of goods completely by autonomous driving. How to give consideration to the current technical limitations and give full play to the advantages of autonomous driving under the limited scenarios so as to achieve the efficient connection them is an urgent problem to be solved.

In this paper, on the basis of the existing research on the theoretical system of underground logistics planning as well as the research and application on the autonomous driving technology, a new freight transport mode combining the autonomous freight transport with underground channel is proposed, so as to make use of the urban underground space to reduce the impact on the current situation of the city as much as possible; the other interferences are avoided by means of special channel and special right of way; in addition, the dual mode combining the manned driving and autonomous driving is adopted to solve the problem in the limitation of the existing autonomous driving technology. The adoption of the autonomous driving in the special channels can improve the transportation efficiency to a great extent. The application of the manned driving in the industrial parks or on the urban roads can improve the transportation safety effectively.

2. Key technologies to planning and design of freight transport system

2.1 Research on Overall Architecture

The underground container logistics system adopts the automated freight transport form to establish a stable, continuous and reliable container transport mode, which is characterized by underground, intelligence, automation, environmental protection and high efficiency. The overall design of the underground automated container transportation system is mainly composed of the transportation equipment, layout of the underground channel, layout of freight terminal, analysis of transport organization, and design of connection with overall operation of the port. Figure 1 is the overall framework diagram for planning and design of the automated freight transport system.

![Figure 1. Design of overall architecture of system](image)
As the core of the whole system, the transportation equipment is used for the container transportation and decisive to the civil structure of the system, and the layout of the channel freight terminal, so that the comparison and selection among the multiple schemes is necessary.

The underground channel is designed mainly to solve the problem of the channel route position selection and channel size. When selecting the channel route position, it is required to determine the starting and ending points as well as the overall route direction of the channel according to the requirements for the traffic streamline of the operations between the port areas. When determining the channel size, it is required to reasonably define the plane and longitudinal section of the route according to the characteristics of the transportation system, and comprehensively determine the cross-sectional spatial layout of the channel on the basis of the driving construction clearance and in combination with the layout requirements for ventilation, fire control and other facilities and equipment.

The layout of the freight transport terminal is the connection and transition area between the underground container logistics system and the logistics operation within the whole port area, realizing the transportation switching of the containers between the channel and port area. The analysis of the transportation organization is mainly used to determine the reasonable container logistics handling technology on the basis of the different transport equipment systems, and verify the matching degree between different parts of the system by means of the relevant simulation.

In addition, the design of the underground container system shall also take into account the design of connection to the overall operation of the port, in order to ensure that the system shall match with the operation of the whole system in the terminal and port, including the connection with the interface in the physical area; the proper consideration shall be given to the traffic organization and the relevant vehicle storage, in order to avoid the impact on the port traffic and the influence on the overall operation in the terminal and port, so as to achieve the comprehensive benefit of “1 + 1 > 2”.

2.2 Transportation Equipment

As the core of the underground container logistics system, the transportation equipment is decisive to the design of the logistics process, the form of the civil structure, and the auxiliary facilities and equipment of the whole system. The transportation equipment used in the underground container logistics system includes AGV, automated container truck, and rail vehicle. Any transportation equipment has its own adaptability and advantages and disadvantages. The comprehensive comparison and selection and research are required to select the reasonable transportation equipment, and reduce the cost of investment and the cost of operation and maintenance as much as possible while ensuring the maturity and feasibility of the technology and meeting the requirement of the transportation capacity.

The design of the underground automated freight transport system proposed in this paper is based on the autonomous driving dual-mode container truck transportation system. In 1980s, Japanese Institute of Public Engineering made research on the application of the electric dual-mode truck in freight transport system, and argued that such systems could mitigate the traffic congestion on the ground and reduce occurrence rate of traffic accidents, and that the use of the electricity as energy could reduce the emission of toxic gas from freight trucks [9].

For the autonomous driving dual-mode container truck, the automatic control system is added onto the traditional container truck, and the V2X technology is used to achieve the remote control of the truck as well as the communication control between the trucks while giving consideration to the autonomous driving mode and manned driving mode in the working condition of manned driving, so as to meet the transportation requirements in different scenarios.

The autonomous driving dual-mode container truck can combine the advantages of the freight subway (automatic control) and the traditional container truck, so as to effectively avoid the problems in lifting and freight transfer at both ends while preventing the people from the access into the tunnel, showing the great advantages in the saving of the civil engineering investment cost, the reduction of the operation and maintenance cost, and the improvement of the transportation flexibility.
The autonomous driving dual-mode container truck is deemed as the development phase between the traditional container truck and the fully autonomous driving container truck, and mature and feasible technically at present. In particular, for this project in a closed tunnel environment without any other interference, the reliability of the control technology is guaranteed at a higher level.

2.3 Underground Channel
The underground channel involves the selection of the route position as well as the design comparison and selection of the channel size. From the perspective of design, the comprehensive consideration shall be given to the vertical design control of the channel, the selection of the starting and ending point, the adaptability to the engineering geology, and the difficulty in construction. From the perspective of engineering economy, it is necessary to consider the construction cost of the project, the land demolition and compensation, the operation and maintenance, and the impact on the surrounding ecological environment and waterways.

When determining the size of the underground channel, it is required to reasonably define the plane and longitudinal section of the route according to the characteristics of transportation system while considering the expected container throughput of the port and the analysis results of the channel capacity, and comprehensively determine the cross-sectional spatial layout of the channel on the basis of the driving construction clearance and in combination with the layout requirements for ventilation, fire control and other facilities and equipment.

In accordance with the transportation requirements of the autonomous driving dual-mode container truck, the unmanned autonomous driving mode is adopted in the underground channel, by which the driver will not enter the underground channel, and the movement of the truck will be controlled completely by computer, so that it is possible to achieve the more precise trajectory control of the truck similar to the rail transit, so as to reduce the lane width and the net lateral width to a great extent; the lane width may be designed as 3.1 m, and the single lane can meet the demand of traffic. For the structural form of the channel, the shield construction method or the open-cut method may be adopted. Due to the unmanned driving inside the underground channel, the standards for ventilation and lighting facilities in the tunnel can be lowered to a great extent. Among others, ventilation facilities may be installed in conjunction with the works to be done at both ends of the shield tunnel, and the general emergency lighting may be provided.

2.4 Transportation Organization
The transportation organization analysis mainly determines the reasonable container logistics handling technology according to the different transportation equipment systems, including the average operation time, the number of trucks to be equipped, the number of cranes to be equipped, and departure time, and verifies the matching degree between different parts of the system through the relevant simulation.

Different transportation equipment systems require different transportation organization modes. The dual-mode scheme is adopted for autonomous driving dual-mode container truck transportation. In the connecting tunnel, there is an interference-free, fully-enclosed, line-fixed, and unmanned land application scenario, so the autonomous driving is used due to the mature technology; after driving out of the tunnel, it will be switched to the manned driving mode. The specific mode is: If the truck is loaded at the loading station, the driver shall drive the truck into the ground switching area, and park at the designated position, and then the truck shall be switched to the autonomous driving mode and drive into the tunnel, and then enter into the ground switching area, and park at the designated position, and then the truck shall be switched to the manned driving mode, and the driver shall drive the truck to the loading station in the port area for unloading; then, the truck shall be loaded, and returned to the ground switching area, and parked at the designated position, and then switched to the autonomous driving mode, and drive into the tunnel.
2.5 Layout of Freight Terminal
The layout of the freight terminal is the connection and transition area between the underground container logistics system and the logistics operation in the whole port area, realizing the transportation transfer of containers between the channel and port area, and composed of the underground yard and the ground yard. The underground yard is mainly used to realize the functions such as direction change, temporary storage and temporary maintenance of the trucks. The ground yard is mainly used to arrange the connection truck and the vertical lifting equipment, as well as the temporary storage space for truck queuing.

The autonomous driving dual-mode truck transportation system of the underground freight transport system proposed in this paper is mainly characterized by establishing the mode switching area to achieve the switching between the autonomous driving mode and the manned driving mode, and separate the functions of the automated areas and the non-automated area strictly; dividing the space with the separation facilities, designating the entrance and exit for the drivers to get on or off the truck, and taking the door access and other measures to ensure that the automated area shall become a fully-closed area; providing the truck guiding system at any truck space in the switching area, and ensuring the parking of the truck at the accurate position in combination with the infrared detection. On the other hand, the truck storage area is established for temporary parking in the peak hours so as to avoid traffic congestion, and play a role of peak clipping.

3. Study on Application Case

3.1 Profile of Project
Currently, the central operation area in operation and the eastern operation area under planning and construction in Yantian Port are separated by a sea area in the width of 1040m; therefore, a connecting channel between such two areas shall be built to realize the coordinated operation in Yantian Port area, and the sharing of the international route transit containers and the streamer equipment. As predicted, the container throughput at Yantian Port will reach 16 million TEUs by 2030, and the maximum annual throughput capacity of the eastern operation area as planned will reach 5 million TEUs.

Calculated according to the traffic capacity, for the connecting channel project in the central operation area and the eastern operation area, the construction scale with two lanes in two ways (two routes) is satisfactory. However, if the bridge scheme and the conventional tunnel scheme (manned driving) are adopted, the conditions for emergency parking and emergency rescue shall be reserved for the channel. Therefore, the bridge scheme and the conventional tunnel scheme need the scale with four lanes in two ways; if the underground container logistics system scheme is adopted, only two lanes shall be provided to meet the requirements. In this paper, the connecting channel between the central operation area and the eastern operation area in Yantian Port under planning and construction is taken as an example to explain in detail the application of the proposed underground automated freight transport system design method for the autonomous driving dual-mode truck in the underground container logistics system in the port area. Figure 2 is the geographical location map and the surrounding schematic diagram for Yantian Port engineering project.
3.2 Route Design

The central and eastern operation area connecting channel project starts at the side of empty container yard in the central operation area and between the Longitude Pathway 3# and the Longitude Pathway 2#, runs northwards to pass through Dapeng Bay, and then runs eastwards to connect to the port area to the north of the eastern operation area. The total length of this channel is approximately 2.66km (See Figure 3). In accordance with the principle of the planar alignment and the control factors, the design center line adopts the design standard that the speed at the main port area shall be 40km/h; on the whole route, there are four intersections; the maximum radius of the circular curve is 500m, the minimum radius of the circular curve is 320m; the maximum length of the straight line is 656.21m, and the minimum length of the straight line is 297.18m.

In order to ensure that after the completion, the channel will not affect the original ground road in the central operation area, the main route will be opened after the Longitude Pathway 2#, and grounded before the Longitude Pathway 3#; there shall be the parking spaces on the north side nearby the Longitude Pathway 3#, in order to facilitate the operation in the future. After passing through the Longitude Pathway 1#, the working well of shield construction shall be set up at a certain interval on the port area to the east of the central operation area, and the working well shall be set up before the port area in the eastern operation area, so as to guarantee that the covering soil of in the shield interval shall be over 6m as a minimum.

The average covering soil of the main route in the shield section is approximately 12m; a working well shall be set up in the central operation area and the eastern operation area respectively with the covering soil in the depth of approximately 6m; in order to guarantee that after the completion, the underground logistics channel shall not affect the operation of the existing roads, the open section in the central operation area shall be opened after the Longitude Pathway 2# with the longitudinal slope of 4.0% and the open section in the length of 187m; it shall be opened after the port area in the eastern operation area with the longitudinal slope of 3.9% and the open section in the length of 176m (see Figure 4).
The cross section of the tunnel in this project is mainly divided into three structural forms, i.e. the cross section of the circular shield tunnel, the cross section of the buried section, and the cross section of the open section.

3.2.1 **Layout of cross section of circular tunnel.** According to the route design, the cross section of the circular shield tunnel adopts the double-hole two-way with a single lane; the width of each lane is 3.1m, the width of the marginal strip is 0.25m, the total width of the truck traffic clearance is 3.6m, and the inner diameter of the circular tunnel is 6.1m.
3.2.2 *Layout of cross section of tunnel in open-cut section.* The single-hole single-layer layout form shall be adopted, and the single lane shall be laid out; the width of each lane is 3.1m. The clearance size of the tunnel in the standard section is 7.45mx4.5m (W x H). The space in the width of 0.25m for decoration, equipment installation and pipeline corridor shall be reserved from either side of the clearance to the side wall. The space in the width of 0.2m for equipment installation shall be reserved from the top of the clearance to the roof. For the layout of the cross section of the tunnel in the open section, the single lane in one way shall be laid out; the width of each lane is 3.1m.

![Figure 7. Standard cross section layout for open section (unit: m)](image)

3.3 *Operation Organization*

3.3.1 *Operation Design.* In order to adapt to the operation mode in the central operation area and the eastern operation area, the intelligent dual-mode container truck scheme is proposed. In the central operation area and the eastern operation area, there are the non-automated terminals; on the basis of the maturity degree of the existing autonomous driving technology, the manned driving is adopted in such area; in the tunnel, there is the interference-free, fully-enclosed, line-fixed, and no man’s land application scenario, so the autonomous driving is used due to the mature technology; if the automated terminals will be constructed in the eastern operation area in the future, the switching area shall be cancelled to achieve the seamless connection.

The dual-mode scheme is adopted for autonomous driving dual-mode container truck transportation. In the tunnel, the unmanned autonomous driving is adopted; after driving out of the tunnel, it shall be switched to the manual mode. The specific mode is (See Figure 8): If the truck is loaded at the loading station in the central port area, the driver shall drive the truck into the ground switching area, and park at the designated position, and then the truck shall be switched to the autonomous driving mode and drive into the tunnel, and then enter into the ground switching area in the eastern port area, and park at the designated position, and then the truck shall be switched to the manned driving mode, and the driver shall drive the truck to the loading station in the port area for unloading; then, the truck shall be loaded, and returned to the ground switching area, and parked at the designated position, and then switched to the autonomous driving mode, and drive into the tunnel.

![Figure 8. Analysis of transportation organization](image)
3.3.2 Design of Ground Switching Area. The ground switching area is composed of the mode switching area, truck storage area, and driver rest and management room. The mode switching area is used to realize the switching between the manned and autonomous driving mode, the parking of the truck at the designated position, and the access of the driver. The truck storage area is used for temporary parking in the peak hours so as to avoid traffic congestion, and play a role of peak clipping; by means of dispatching, the truck shall drive into the mode switching parking area as required.

![Figure 9. Schematic Diagram for Setup of Ground Switching Area](image)

The automated areas and the non-automated area shall be separated strictly; the space shall be divided with the separation facilities, and the entrance and exit shall be designated for the drivers to get on or off the truck, and the door access and other measures shall be taken to ensure that the automated area shall become a fully-closed area; the truck guiding system shall be provided at any truck space in order to ensure the parking of the truck at the accurate position in combination with the infrared detection. Furthermore, the driver shall drive off or get off the truck when the system prompts for confirmation. In the switching area, four lanes in two ways are provided; under normal circumstances, one lane is used for parking while the other lane is used for backup. The automatic control area is physically isolated from the non-automatic control area.

![Figure 10. Schematic diagram for dual-mode switching design](image)

![Figure 11. Cross section of switching area](image)
3.3.3 Operation Dispatching Mode. The operation dispatching mode is described as follows:

- In the central port area, the driver shall switch the truck to the driver mode, and move the truck from the ground switching area to the operation area for operation.
- With the dispatching server, the truck management center will issue the instruction of convoy driving of trucks in tunnel. The drivers will follow the instruction from the management center and park the trucks in sequence, then leave the trucks after selecting the unmanned driving mode. After the confirmation by the dispatching center, the driving of the trucks in the tunnel will start.
- After driving out of the tunnel, the trucks will park and drive in convoy at the predetermined positions; the dispatching center will inform the drivers in the eastern port area to take over the trucks, and dispatch the operation of the trucks.
- After completing the operation, the dispatching center will issue the instruction of trucks marshalling in convoy; the drivers will park the trucks at the designated positions in sequence according to the instruction from the dispatching center.
- The dispatching center will issue the instruction of unmanned driving of the trucks in the tunnel, and the trucks shall drive in an unmanned manner; the dispatching center will inform the drivers in the eastern port area to take over the trucks, and dispatch the operation of the trucks.

![Figure 12. Schematic Diagram for Operation Dispatching Mode](image)

3.4 Transport Trucks

The autonomous driving dual-mode container truck is in the development phase of conditional autonomous driving, which takes into account the advantages of the track (Automatic control, virtual track) and traditional container truck, so as to avoid the problems in lifting and transfer at both ends, prevent the people from access into the tunnel, save the civil engineering investment cost, and reduce the cost of operation and maintenance, as well as enhance the flexibility of transportation. With regard to the traditional container truck, the chassis of 6X4 Dongfeng heavy tractor is taken as an example, and the main parameters of the truck are shown as follows:

| No. | Item                  | Indicators                                  |
|-----|-----------------------|---------------------------------------------|
| 1   | Length of truck body  | 6.96m (Without trailer)                     |
| 2   | Width of truck body   | 2.5m                                        |
| 3   | Height of truck body  | 3.77m                                       |
| 4   | Mass of whole truck   | 8.8t                                        |
| 5   | Total traction mass   | 40t                                         |
| 6   | Maximum speed         | 80km/h (Working condition of port, maximum design speed) |
| 7   | Maximum gradient (%)  | ≥20                                         |
| 8   | Maximum turning diameter | Larger than 16m (With trailer)               |

In order to satisfy the requirements for functions and performances of the smart truck, on the basis of the integration of the key executive systems of the basic prototype truck, a complete set of smart truck system scheme shall be designed in order to achieve the autonomous driving function of the
smart truck. This system consists of four parts, i.e. the environment perception system, intelligent decision-making and control execution system, connectivity, and human-computer interaction system.

4. Conclusions
In this paper, a new type of underground channel freight transport system based on the autonomous driving dual-mode container truck is proposed, in order to make full use of urban underground space to reduce the impact on the current situation of the urban traffic and environment. Furthermore, the dual-mode transportation form combining the manned driving and the autonomous driving is adopted to effectively solve the problem in the limitation of the existing autonomous driving technology; the autonomous driving on the special channel may improve the efficiency of transportation to a great extent; the manned driving in the industrial parks or on the urban roads may improve the transportation safety effectively.

Taking the connecting channel between the central operation area and the eastern operation area in Yantian Port as the example, the overall design of the underground freight transport system based on the autonomous driving dual-mode container truck is made, including the allocation of the transportation equipment, the layout of the underground channel, the layout of the freight terminal, the analysis of the transportation organization, and the design of connection with overall operation at the port. This study can provide a reference not only for the automated container freight transport linked with the port, but also for the relevant design of the smart logistics park in the future.

Acknowledgments
This study is supported by Shanghai Science and Technology Committee Research Project (No. 16DZ1201403 and No. 18ZC2424000), by National Science Foundation of China under Grant No. 51508321, and by the Shanghai Rising-Star Program under Grant No. 15QB1403600.

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