Supplementary Material

Application of a digital twin for highway tunnels based on multi-sensor and information fusion

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# Supplementary Figures and Tables

**Supplementary Table 1 Collection methods and requirements of highway tunnel operation data**

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| --- | --- | --- |
| **Data** | **Collection methods** | **Sensor Installation Requirements** |
| Speed data | Vehicle Detection Sensor | 1. When using induction coil detection sensors, the spacing should be arranged between 300-750 meters.2. Vehicle detection sensors（radar, microwave, LiDAR fusion sensors, etc.) should be set up to prevent other equipment or objects from blocking. |
| Traffic volume data | Vehicle Detection Sensor |
| Percentage of lane occupancy data | Vehicle Detection Sensor |
| Vedio data | Video image sensor | 1. The video image sensor outside the tunnel should be set at the entrance and exit of the tunnel between 100-250 meters.2. For the video image sensor inside the tunnel, a spacing of 100-200 meters should be used at a distance of 2-5 meters from the entrance, and the recommended setting is 120-150 meters. |
| Carbon monoxide data | Carbon monoxide detection sensor | 1. For tunnels with jet fans for longitudinal ventilation, they should be set up in the middle, at the bends and a distance of 100-150 meters from the exit.2. For tunnels with vertical and inclined shaft ventilation, they should be set up 30 meters in front of the exhaust port.3. The detection sensor is installed on the outer side wall bracket of the tunnel, with a height of 2.5-3 meters from the maintenance road. |
| Visibility data | Visibility detection sensor |
| Nitrogen dioxide data | Nitrogen dioxide detection sensor | The detection sensor is installed on the outer side wall bracket of the tunnel, with a height of 2.5-3 meters from the maintenance road. |
| Light intensity dataoutside the tunnel | Light Intensity Detection Sensor | Light intensity detection sensor outside the tunnel is installed outside the tunnel, a distance of one parking line of sight (100-200 meters) from the tunnel entrance. |
| Light intensity dataiutside the tunnel | Light Intensity Detection Sensor | Light intensity detection sensor inside the tunnel is installed inside the tunnel, 20-25 meters away from the tunnel entrance. |
| Wind speed and direction data | Wind speed and direction detection sensor | 1. For tunnels with jet fans for longitudinal ventilation, they should be set up at the bends and a distance of 100-150 meters from the exit.2. For tunnels with vertical and inclined shaft ventilation, they should be set up 30 meters in front of and behind the exhaust and supply air outlets.3. The detection sensor is installed on the outer side wall bracket of the tunnel, with a height of 2.5-3 meters from the maintenance road or installed on the nails on both sides of the inside and outside of the tunnel, and the two probes make an angle of 30° to 60° with the longitudinal center line of the tunnel, preferably 45°, and cannot encroach on the building clearance. |
| Traffic Event Data | Event Monitoring Sensor | 1. Setting principles refer to video image sensors.2. It is recommended to repurpose existing video image sensors. If using fusion perception devices, they can replace the original video image sensors. |

**Supplementary Table 2 Characteristics of highway tunnels operation data**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Tunnel environment** | **Direction data** | **Data units** | **Data Range** | **Data** **accuracy** | **Data transmission cycle** |
| Ventilation environment monitoring | Visibility data | m-1 | 0 ~ 0.0015m-1 | $\pm 0.0002$m-1 | 5～10min |
| Carbon monoxide data | 10-6（ppm） | 0~300x10-6(0 ~ 300ppm) | $\pm $2x10-6($\pm $2ppm) | 5～10min |
| Wind speed and direction data | m/s | -20 ~ +20m/s | $\pm 0.2$m/s | 5～10min |
| Nitrogen dioxide data | 10-6（ppm） | 0-10 cm3/m3 | $\pm 5\%$ indicated value | 5～10min |
| Lighting environment monitoring | Light intensity dataoutside the tunnel | cd/m2 | 1～6500cd/m2 | $\pm 3\%$ indicated value | 5～10min |
| Light intensity dataiutside the tunnel | lx | 1~1000lx | $\pm 3\%$ indicated value | 5～10min |
| Traffic environment monitoring | Speed data | Km/h | 5～2000km/h | accuracy$\geq $85% | 5～10min |
| Traffic volume data | Vehicle /h | - | accuracy$\geq $85% | 5～10min |
| Percentage of lane occupancy data | Vehicle /km | - | accuracy$\geq $85% | 5～10min |

**Supplementary Table 3 1D-CNN-LSTM model parameters**

|  |  |
| --- | --- |
| **Layers** | **Parameters** |
| Convolutional layers | Filter = 20, Kernel-size = (10,1), Stride = 1 |
| Max pooling layer + dropout（0.15） | Pool-size = (2,1), Stride = 2 |
| Convolutional layers | Filter = 40, Kernel-size = (5,1), Stride = 1 |
| Max pooling layer + dropout（0.15） | Pool-size = (2,1), Stride = 2 |
| Convolutional layers | Filter = 80, Kernel-size = (3,1), Stride = 1 |
| Max pooling layer + dropout（0.15） | Pool-size = (2,1), Stride = 2 |
| LSTM | Hidden-size = 64 |

**Supplementary Table 4 Test results**

|  |  |  |
| --- | --- | --- |
| **Models** | **RMSE** | **Reduce** |
| CNN-LSTM-BASE | 0.01254 | 0 |
| CNN-LSTM-ECA | 0.00526 | 58% |
| CNN-LSTM-SE | 0.00036 | 97% |
| CNN-LSTM-CBAM | 0.00023 | 98% |
| CNN-LSTM-TPA | 0.00015 | 99% |

**Supplementary Table 5 Code of basic tunnel parameter table**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Abbreviation** | **Data types** | **Can be Null** | **Notes** |
| Tunnel Name | TunName | Varchar(20) | False |  |
| Tunnel Beginning number | TunBegin | Numeric(7,3) | False | Unit: Kilometer |
| Tunnel ending number | TunEnd | Numeric(7,3) | False | Unit: Kilometer |
| Tunnel Central number | TunCentre | Numeric(7,3) | False | Unit: Kilometer |
| Classification code | ClaCode | Varchar(20) | False |  |
| Length | Length | Numeric(6,2) | False | Unit: Kilometer |
| Clear width | CleWidth | Numeric(6,2) | False | Unit: meter |
| Clear height | CleHeight | Numeric(6,2) | False | Unit: meter |
| Hole Mode | HoMode | Varchar(20) | False |  |
| Mode of the cross-section | SecMode | Varchar(20) | False |  |
| Lining material | LinMaterial | Varchar(20) | False |  |
| Mode of lighting conditions | LighMode | Varchar(20) | False |  |
| Mode of ventilation | VenMode | Varchar(20) | False |  |
| Mode of electromechanical facilities | FaciMode | Varchar(20) | False |  |
| Completion date | ComDate | Datetime | False |  |
| Design unit | DesUnit | Varchar(20) | False |  |
| Construction unit | ConsUnit | Varchar(20) | False |  |
| Supervision unit | SupUnit | Varchar(20) | False |  |
| Management unit | ManUnit | Varchar(20) | False |  |
| Maintenance unit | MainUnit | Varchar(20) | False |  |
| Name of the sender | SendMan | Varchar(20) | Yes |  |
| Date and time | SectTime | Datetime | Yes |  |
| Vehicle detection sensor ID | VDID | Varchar(20) | False |  |
| Collection time | RecTime | Datetime | False |  |
| Collection cycle | RerPeriod | Smallint | Yes |  |
| Upstream heavy vehicle flow | UupFluxB | Smallint | Yes |  |
| Upstream light vehicle flow | UupFluxS | Smallint | Yes |  |
| Upstream flow | UupFlux | Smallint | Yes | Total traffic volume of all lanes in the upstream direction |
| Downstream heavy vehicle flow | DwFluxB | Smallint | Yes |  |
| Downstream light vehicle flow | DwFluxS | Smallint | Yes |  |
| Downstream flow | DwFlux | Smallint | Yes | Total traffic volume of all lanes in the downstream direction |
| Upstream average speed | UpSpeed | Smallint | Yes |  |
| Downstream average speed | DwSpeed | Smallint | Yes |  |
| Upstream average occupancy rate | UpOccup | Numeric(5,2) | Yes |  |
| Downstream average occupancy rate | DwOccdown | Numeric(5,2) | Yes |  |
| Total number of lanes | LaneNum | Tinyint | Yes | Number of lanes detected by the equipment |
| Working status | Status | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Communication status | CommStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Carbon monoxide and visibility detection sensor ID | COVID | int | False |  |
| Collection time | COVTime | Datetime | False |  |
| Collection period | COVPeriod | Smallint | Yes |  |
| Carbon monoxide concentration | COConct | Smallint | Yes |  |
| Visibility | Visibility | Smallint | Yes |  |
| Working status | WorkStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Communication status | CommStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Light intensity detection sensor ID | LOLIID | int | False |  |
| Acquisition time | LOLITime | Datetime | False |  |
| Acquisition period | LOLIPeriod | Smallint | Yes |  |
| Outside brightness of the hole | LOLumi | Smallint | Yes |  |
| Inside brightness of the hole | LILumi | Smallint | Yes |  |
| Working status | WorkStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Communication status | CommStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Wind speed and direction detection sensor ID | WSID | int | False |  |
| Collection time  | WSTime | Datetime | False |  |
| Collection cycle  | WSPeriod | Smallint | Yes |  |
| Wind direction  | Direction | Tinyint | Yes |  |
| Wind speed  | Speed | Smallint | Yes |  |
| Working status  | WorkStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |
| Communication status  | CommStatus | Tinyint | Yes | 0-normal, 1-fault, 2-unknown |

**Supplementary Table 6** **Description of digital twin system for highway tunnel operation**

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| **Subsystem** | **Function name** | **Description** |
| Comprehensive monitoring system | Tunnel daily management control | According to the monitoring center, the selected tunnels within its jurisdiction can realize the functions of tunnel electromechanical equipment status, detection information collection, single control, group control, event monitoring, and alarm information confirmation, event and fault information entry in a three-dimensional and two-dimensional visual model. |
| Digital Twin System | Tunnel basic information digital twin | The digital twin presents the basic information of the tunnel. |
| Digital Twin System | Field electromechanical equipment digital twin | The digital twin presents and controls the electromechanical equipment outside the tunnel and related road sections. |
| Digital Twin System | Comprehensive environmental information digital twin | The digital twin presents the environmental monitoring information of the tunnel and related road sections. |
| Digital Twin System | Real-time traffic operation digital twin | The digital twin presents the real-time traffic flow and vehicle information of the tunnel and related road sections. |
| Digital Twin System | Traffic incident digital twin | The digital twin presents the tunnel event detection. |
| Digital Twin System | Emergency linkage digital twin | The digital twin presents the emergency linkage control plan of the tunnel. |
| Specialized control system | Video inspection special item | The cameras of the selected road sections and tunnels are grouped into 16 video streams for broadcasting and the situation inside the tunnel is inspected. |
| Specialized control system | Tunnel lighting special item control | Remote control, manual control, intelligent control, and contingency control can be selected for the selected tunnels' lighting control. |
| Specialized control system | Road guidance special item control | Graphically display the variable information identification settings of the tunnel's surrounding road network, display the current display content of each variable information sign, and support manual and contingency information release and single or group release per the contingency plan. |
| Specialized control system | Electromechanical equipment linkage control | The linkage control plan can be customized based on the tunnel's actual needs, and the control modes are accident linkage control mode and daily linkage control mode. |
| Command and Control System | Linkage emergency plan management | The graphical interface realizes the linkage control plan for tunnel electromechanical equipment, and add/delete/modify/query functions are available. |
| Command and Control System | Emergency special plan management | The graphical interface realizes the emergency plan for tunnel events, and add/delete/modify/query functions are available. |
| Command and Control System | Operation log | The operation records of the current system users can be viewed. |
| Maintenance Management System | Maintenance task management | Tunnel electromechanical system maintenance task management (daily inspection, regular maintenance, periodic maintenance task formulation), tunnel maintenance plan formulation. |
| Maintenance Management System | Electromechanical equipment fault management | Manage faulty electromechanical equipment and fault repair tasks. |
| Maintenance Management System | Data management | Manage tunnel electromechanical system-related contracts and knowledge base. |
| Maintenance Management System | Operation log | The operation records of the current system users can be viewed. |
| Data analysis system | Operation theme data statistical analysis | By collecting, summarizing, comparing, and analyzing operation-related data, statistical and analytical reports in predetermined or customizable formats can be generated. |
| Data analysis system | Traffic theme data statistical analysis | By collecting, summarizing, comparing, and analyzing traffic-related data, statistical and analytical reports in predetermined or customizable formats can be generated. |
| Data analysis system | Equipment data statistical analysis | By collecting, summarizing, comparing, and analyzing electromechanical equipment-related data, statistical and analytical reports in predetermined or customizable formats can be generated. |
| Data analysis system | Dashboard - operation data display | Traffic theme, energy-saving theme, environmental theme, and equipment status data display. |
| Data analysis system | Dashboard - electromechanical equipment automatic inspection | Inspect the working status of tunnel electromechanical equipment online and automatically discover abnormal devices. |
| Data analysis system | Dashboard - emergency command | Event detection, alarm confirmation, video call, and contingency plan selection and demonstration. |
| Data analysis system | Operation log | The operation records of the current system users can be viewed. |
| Backend management system | Role information management | The platform’s organization structure management, personnel management, full selection management, and user management are available. |
| Backend management system | Basic data management | Manage electromechanical equipment, contract unit, equipment manufacturer, emergency facilities, and external units management. |
| Backend management system | Platform log management | The operation records of the current system users can be viewed. |