CONFLICT RESOLUTION OF CONNECTED TRUCKS AT INTERSECTION IN OPEN-PIT MINE

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In the development and construction of intelligent mine unmanned transportation system, traffic control at unsignalized intersection has strong scene particularity and collaborative control requirements. In order to solve the conflict risk caused by unmanned mining trucks at unsignalized intersections and ensure the safety and efficiency of transportation system, this paper designed a conflict resolution method based on vehicle-road cooperative system. The control objectives were determined by conflict detection model according to safety margin and multi-level right-of-way decision. The cooperative control algorithm of traffic risk minimization based on model predictive control (MPC) method was designed. The driving strategy of target vehicles was obtained by combining the vehicle driving constraints obtained by fuzzy reasoning with the nonlinear constraint optimization problem for conflict resolution. The simulation results showed that the control method can ensure that multiple vehicles synergistically passing the unsignalized intersection under the premise of the minimum set safety distance, and it has timely and effective adaptability to the comprehensive influence of weather change, road quality and dust concentration.

Keywords: open-pit mine; connected trucks; unsignalized intersection; conflict resolution; MPC

1. Introduction

Intelligent mine construction is the national development progress of the urgent priority. It fulfills the strong demand of society for energy and resources which is consistent with sustainability and greater safety [1]. By 2025, open-pit coal mines will achieve intelligent continuous operations and unmanned transportation in Guiding Opinions on Accelerating the Intelligent Development of Coal Mines [2]. At present, the research of intelligent mine driverless technology mainly contains communication technology, positioning technology, path planning algorithm and vehicle control [3]. The research focuses on the unmanned operation

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function of a single vehicle in a few experimental operational applications during small-scale unmanned transport production stage in China. Unmanned transport systems make it easier to avoid vehicle conflicts through centralized dispatching and fleet scheduling in this case. Therefore, it will become increasingly important with the development of intelligent mine unmanned transportation systems to solve the problem of vehicle conflicts at unsignalized intersections.

The problem of vehicle traffic control at signal-less intersections is a hot research topic in urban transportation intelligent traffic systems. The probability of vehicle accidents at unsignalized intersections is much higher than at other intersections in the urban traffic environment statistics [4-5]. Besides, it also performs a higher level of collaborative optimization. It is divided into centralized optimization control and distributed optimization control, trajectory optimization and right-of-way yielding based on the way of control policy generation [6]. Vehicle speed strategy is optimized based on integrated multi-vehicle motion information in trajectory-based optimization. Ismail H et al used a game theoretic heuristic optimization algorithm to optimize autonomous vehicle passage based on cooperative adaptive cruise control (CACC) [7]. Kamal et al. proposed a vehicle intersection coordination scheme (VICS) based on model predictive control (MPC). It dissipates the conflict by separating the arrival time of conflicting vehicles to the conflict point to obtain the optimal vehicle trajectory [8-9]. Wu Z et al. proposed a collision avoidance strategy based on vehicle-vehicle communication technology in the scenario of a typical two-way two-lane unsignalized intersection [10].

Because of unstructured road, it failed to fully apply to mine road environment with the above research results in urban traffic environment without lane line and lane mark, with poor quality and changeable adhesion coefficient. Therefore, we design the safety assisted decision making system based on MPC for passage risk minimization with considering the dynamic response characteristics of heavy-duty trucks, the harsh environmental factors in open pit mines and the passage efficiency of transportation trucks. A driving risk field model under unmanned transportation conditions in open-pit mines is constructed. The purpose of driving safety and improving traffic efficiency of unmanned vehicles in mining areas has been realized under the control of the right-of-way assignment and path planning modules the preprocessed data of vehicle information.

2. Decision-making system for intersection conflict based on intelligent network of mining trucks

2.1 Analysis of intersection conflict in mining area

Referring to the Surrogate Safety Assessment Model (SSAM) [11] rules for determining the type of traffic conflicts, the distribution of vehicle conflict types at two-way two-lane intersections is obtained, When the lane and route information of the vehicle are not available, the absolute value of the difference in front angle between the two vehicles $|\Delta\theta|$ can be used. Traffic conflicts are divided into three types: rear end collision, lane change conflict and intersection conflict. The range of angles is shown in Table 1. When the lane and route information of the vehicle are available, if two vehicles occupy the same lane before and after the conflict, it is a rear end conflict; If one of the vehicles conflicts when changing lanes based on the original route, it is a lane change conflict; If a vehicle changes its route during a conflict, only based on $|\Delta\theta|$ Judgment (where conflicts starting from the same lane only consider rear end conflicts and lane changing conflicts).

Taking a two-lane intersection as an example to further represent the types of conflicts, as shown in Fig. 1.where Ω represents the range of action of the control system.

Table 1

Types of traffic conflicts

Types of traffic conflicts	$\|\Delta\theta\|$
Rear end conflict	$0° \le \|\Delta\theta\| \le 30°$ or $300° \le \|\Delta\theta\| \le 360°$
Lane change conflict	$30° \le \|\Delta\theta\| \le 85°$ or $275° \le \|\Delta\theta\| \le 330°$
Intersection Conflict	$85° \le \|\Delta\theta\| \le 275°$

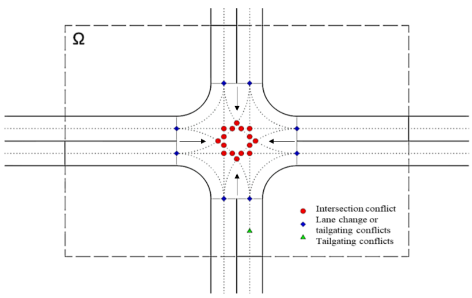


Fig. 1. Vehicle conflict type distribution diagram

In accordance with the Coal Mine Safety Regulations [12] and other relevant regulations, overtaking behavior is prohibited and measures should be taken to slow down the car behind avoid tailgating. Conflicts are dissipated according to the right-of-way of the vehicle, for intersecting conflicts and lane change conflicts. Vehicles traveling on weak rights-of-way should be slowed down which combined with the actual situation that vehicles in open-pit mining areas generally travel in accordance with the speed limit standards.

2.2 Vehicle conflict state detection model

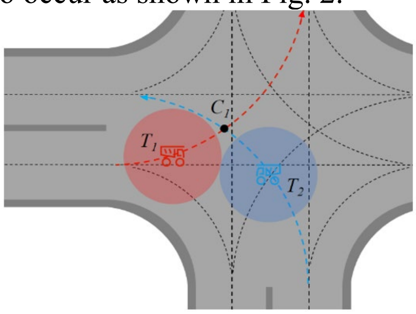
The trajectory of the vehicle is required to be judged in order to infer the conflict situation considering vehicle collision conflicts. In this paper, we choose a circular model that can reflect the shape and size of vehicles, and combine the characteristics of similar shape of transportation vehicles in open pit mines. Adding safety margin information to the vehicle form factor, the detection model of vehicle i and vehicle j is obtained

$$\sqrt{\left(x_i(t_i) - x_j(t_j)\right)^2 + \left(y_i(t_i) - y_j(t_j)\right)^2} = R_i + R_j \quad (1)$$

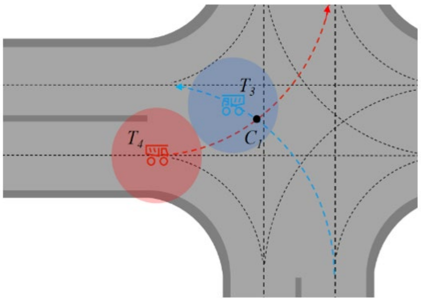
where $R_i = \frac{1}{2}\sqrt{L_i^2 + W_i^2} + R_{safe_i}$,and it is radius circular model of vehicle i, similarly with R_j. t_i and $t_j$refer to the time when vehicle i and vehicle j arrive at the conflict position, respectively, $x_i(t)$ and $y_i(t)$ represent the horizontal and vertical position coordinates of vehicle i, R_i is the radius of circular model of vehicle i, L_i and W_i are the length and width of vehicle i, respectively and R_{safe_i} is the safety margin corresponding to vehicle i.

2.3 Multilevel right-of-way decision model

For unmanned transportation scenarios in open pit mines, a right-of-way decision model based on rules for determining right-of-way relationships realizes more purposeful signal-free intersection access control effects. For the safety margin-based circle detection model used in this paper, two scenarios may occur when a conflict is predicted to occur as shown in Fig. 2.



(a) No trucks arrive at the intersection



(b) One truck arrives at the intersection first

Fig. 2. Two conflict detection results

The intersection of the vehicle T_1 with the $T_2$and the T_3 and the T_4 is the point of C_1, where only the T_3 is the exit path intersection. At this time, if the priority of the judgment T_3 is less than T_4 (such as T_3 no load, T_4 load), then only the T_3 that is driving at the specified speed can be given a deceleration command, which will lead to a more serious conflict between the two vehicles. T_3 the conflict with the T_4

is greatly extended, and eventually lead to a large and long-term deceleration of the T_3, which has a more serious impact on the overall transportation system.

The first arriving vehicle is determined by the change in distance between the vehicle and the intersection, which is expressed as:

$$D_{T_i c_j}(t + \Delta t) - D_{T_i c_j}(t) > 0 \quad (2)$$

where t is the predicted moment of conflict occurrence, $D_{T_i c_j}(t)$ is the distance between vehicle T_i and path intersection c_j at moment t, and Δt is the sampling time interval of the prediction system.

3. Auxiliary safety decision algorithm for traffic risk minimization

Researchers have proposed the concept of Artificial Potential Field (APF) for vehicle path planning, obstacle avoidance, and follow-the-lead models [13-15] in the exploration of research on vehicle safety decision methods. Therefore, the concept of kinetic energy field and potential energy field is introduced, which is improved according to the special working conditions of open pit mines, as the basis for safety optimization of cooperative optimal control of signal-free intersections.

3.1 Risk field model of connected trucks in open-pit mining area

The kinetic energy field formed at the coordinates (x_j, y_j) has the field strength $\boldsymbol{E}_{V\_ij}$ with defining vehicle i and center-of-mass coordinates (x_i, y_i).

$$\boldsymbol{E}_{V\_ij} = \frac{GR_i M_i}{|\boldsymbol{r}_{ij}|^{k_1}} \frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|} \exp[k_2 v_i \cos(\theta_i)] \quad (3)$$

where $\boldsymbol{r}_{ij} = (x_j - x_i, y_j - y_i)$, k_1Б k_2Б G are constants greater than 0, M_i is the equivalent mass of vehicle i, R_i is the influence factor of road conditions at (x_i, y_i), v_i is the velocity of vehicle i and θ_i is the angle between the velocity direction of vehicle i and $\boldsymbol{r}_{ij}$. $\boldsymbol{E}_{V\_ij}$ decreases the fastest speed along the field strength direction field strength. When the speed is certain, the smaller the absolute value of the angle θ_i, $\boldsymbol{E}_{V\_ij}$ the larger. It means that the higher the risk of travel.

The equivalent mass M_i is defined as following equation.

$$M_i = T_i\, m_i \left(1 + \sum_k \alpha_k v_i^{\beta_k}\right) \quad (4)$$

where $m_{i,c}$ means unladen, $m_{i,t}$ means load, m_i is the mass of vehicle i, which is taken according to the loading situation, T_i is the type of vehicle i, which distinguishes the different losses caused by different types of vehicle collisions, α_k Б β_k are the constants to be determined and k is the number of terms of the velocity polynomial.

Stationary objects that affect the movement of transport vehicles can be divided into two categories in the mine road environment. The first type of stationary objects are stationary objects that can collide with vehicles within the road range, such as temporarily parked vehicles, safety barriers, etc. The second type of stationary objects are stationary objects that do not substantially collide with vehicles at the boundaries of the road range or outside, while act as constraints on vehicle driving, such as signal base stations.We define the potential energy field formed around the first class of stationary objects $i(x_i, y_i)$ in which the field strength at (x_j, y_j) is $\boldsymbol{E}_{R1\_ij}$.

$$\boldsymbol{E}_{R1\_ij} = \frac{GR_iM_i}{|\boldsymbol{r}_{ij}|^{k_1}}\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|} \tag{5}$$

We define the second type of stationary object, such as the field strength of the potential energy field $\boldsymbol{E}_{R2\_ij}$ formed by signal base station i at (x_j, y_j).

$$\boldsymbol{E}_{R2\_ij} = S_i\frac{GR_iM_i}{|\boldsymbol{r}_{ij}|^{k_1}}\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|} \tag{6}$$

where S_i is the signal base station control range coefficient, the value is 1 only when it is within the corresponding range, and the value is 0 in other cases and $\boldsymbol{r}_{ij}$ react only (x_j, y_j) to the distance to the intersection, in the opposite direction to the lane.

In summary, the field strength of the comprehensive driving risk field at vehicle i under the transportation conditions of the mine is $\boldsymbol{E}_{s\_j}$.

$$\begin{aligned}\boldsymbol{E}_{s\_j} &= \boldsymbol{E}_{V\_j} + \boldsymbol{E}_{R\_j} \\ &= \sum_n \boldsymbol{E}_{V\_ij} + \sum_m \boldsymbol{E}_{R1\_ij} + \sum_m \boldsymbol{E}_{R2\_ij}\end{aligned} \tag{7}$$

3.2 Constraints influenced by environmental factors

It is necessary to make detailed constraints on the driving speed and acceleration of mine cars to ensure driving safety. In the Coal Industry Surface Mine Transportation Engineering Design Standard-GB 51282-2018 [16]. The restricted speed for mining trucks is 40km/h in trunk road, 35km/h in feeder roads, 30km/h in Liaison line roads and 20km/h in Maintenance and overhaul operation area, loading and unloading operation area, intersection.The general relationship between the maximum vehicle acceleration a_{max} and the ground friction coefficient has been obtained as in Eq. 8 [17].

$$a_{max} = g\mu \tag{8}$$

where g is the acceleration of gravity and μ is the ground friction coefficient. The friction coefficient of clay-caked gravel pavement is taken as the value of 0.4 ~ 0.6 referring to the Standard. We can get the maximum acceleration a of 5.88 $\mathrm{m/s^2}$ when the road condition is best.

In the transportation environment of open pit mines, there are three main influencing factors: weather, road quality, and dust concentration [18]. It is assumed that the environmental factors have the same pattern of influence on the maximum acceleration and maximum speed of the vehicle driving.

$$f_c = F(w, rc, dt) \tag{9}$$

where f_c is the current environmental suitability maximum constraint factor, w is the weather, rc is the pavement quality and dt is the dust concentration. A triangle fuzzier is used to blur the input and output.

3.3 Risk minimization of auxiliary decision algorithm based on model predictive control

1) Vehicle longitudinal motion model

In the assumed unmanned transportation environment of open-pit mines in this article, all unmanned vehicles can accurately track their operating routes through a vehicle road coordination system. In this case, for the resolution of conflicts at unsignalized intersections, only optimal control of vehicle speed is needed to achieve safe and efficient passage. Therefore, it is necessary to establish a vehicle longitudinal motion control model. And in order to comply with the characteristics of model predictive control digital control, a discrete time state equation for vehicle longitudinal motion is established, as shown in the Eq.10:

$$s_i(t+1) = s_i(t) + v_i(t)\tau + \frac{1}{2}a_i(t)\tau^2 \quad (10)$$

$$v_i(t+1) = v_i(t) + a_i(t)\tau$$

where $s_i(t)$ is the distance traveled by vehicle i from time 0 to time t, $v_i(t)$ is the speed at vehicle i is traveling at time t, $a_i(t)$ is the acceleration of vehicle i at time t.

2) Constraint Settings

To ensure the feasibility of the control algorithm, the following constraints are introduced.

(1) Vehicle acceleration constraint. Define the vehicle acceleration constraint as shown in the Eq.11:

$$a_{min} \leq a_i(t) \leq a_{max,} \ \forall i = 1,2,\dots N \quad (11)$$

where $a_{max,}$ is the maximum acceleration of the vehicle, obtained by referring to Eq.8 , a_{min} is the minimum acceleration of the vehicle.

(2) Vehicle speed constraints. Vehicle speed constraints should include maximum and minimum speeds to ensure driving safety and transportation efficiency. At the same time, there should also be a corresponding maximum turning speed when turning to avoid accidents such as rollovers. The constraints of velocity in straights and corners are as follows in the Eq.12.

$$v_{min}(t) \leq v_i(t) \leq v_{max}(t) \quad (12)$$

$$v_i(t) \leq v_{cmax}$$

where v_{max} is the maximum speed, v_{min} is the minimum speed, v_{cmax} is the maximum turning speed.

(3) Actual restraint of safe head

In order to avoid rear end collision of vehicles in the same lane after speed regulation of some vehicles, safety headway constraints are set. Define the safe headway h=5. Taking vehicles i and j as examples (vehicle i is the vehicle in front of vehicle j), then the motion of vehicle j must satisfy an inequalityEq.13.

$$v_j(t)h + \frac{1}{2}a_j(t)h^3 < D_{ij}(t) \quad (13)$$

where $D_{ij}(t)$ is the distance between vehicles i and j at time t.

(4) Minimum distance between conflicting vehicles

For vehicles that may be in conflict, assuming vehicles i and j, set qualitative collision avoidance conditions, that is, the minimum distance between conflicting vehicles is as shown in following.

$$D_{ij}(t) > R_i + R_j \tag{14}$$

(5) Turning constraint

The vehicle will generate lateral acceleration when turning, which is provided by the lateral force exerted by the tires on the ground and the lateral slope of the ground. The relationship between the lateral acceleration ac of a vehicle when turning and the vehicle speed and turning radius can be simply expressed as following.

$$a_c = \frac{v_c^2}{R_c} \tag{15}$$

where R_c is the minimum turning radius, v_c is the linear speed of the vehicle along the curve. The relationship between safe turning speed and turning radius on urban roads is specified in the intersection design manual. In the open pit mine road, the safe speed design of the intersection can meet the lateral acceleration requirements of the vehicle turning.

3.4 Optimization objective function design for minimizing traffic risk

The control index of the system is reflected by designing an optimized objective function in the model predictive control algorithm, and the control index can generally be expressed as following [19].

$$J(\tilde{\boldsymbol{x}}, \tilde{\boldsymbol{u}}) = \sum_{t_p=1}^{N_p} \tilde{\boldsymbol{x}}^T\left(k + t_p \middle| k\right)\boldsymbol{Q}\tilde{\boldsymbol{x}}(k + i|k) + \sum_{t_c=1}^{N_c} \tilde{\boldsymbol{u}}^T(k + t_c|k)\boldsymbol{R}\tilde{\boldsymbol{u}}(k + t_c|k)$$

(16)

where N_p is the prediction time domain, N_c is the control time domain, $\tilde{\boldsymbol{x}}$ is the system state quantity, $\tilde{\boldsymbol{u}}$ is the system control quantity, **Q** is the weight matrix on the system state quantity, **R** is the weight matrix on the control quantity and k is the current moment [19].

$$\min_{u(t)} J = \sum_{t=0}^{N_p-1} \sum_{i=1}^{N} K_1 a_i^2(t) + \sum_{t=0}^{N_p-1} \sum_{i=1}^{N} K_2(v_i(t+1) - v_d)^2$$
$$+ \sum_{t=0}^{N_p-1} \sum_{i=0}^{N-1} \sum_{j=i+1}^{N} K_3 \boldsymbol{F}_{i,j}^2(t) + \sum_{t=0}^{N_p-1} \sum_{i=1}^{N} K_4 \boldsymbol{E}_{S\_i}^2 \tag{17}$$

where v_d is the desired speed, K_1 represents the acceleration term weight coefficient, K_2 means the velocity term weight coefficient, K_3 is the weight coefficient of collision terms and K_4 is the risk field item weight factor.

The algorithm architecture of the traffic safety auxiliary decision-making system is shown in Fig. 3. The inputs contain basic vehicle information, driving information and environmental condition information. The vehicle uses the Multi-access Edge Computing (MEC) road detection unit to detect whether the vehicle is in the control range by broadcasting data. Safety-assisted decision control of conflicting vehicles is performed based on a multi-level decision process.

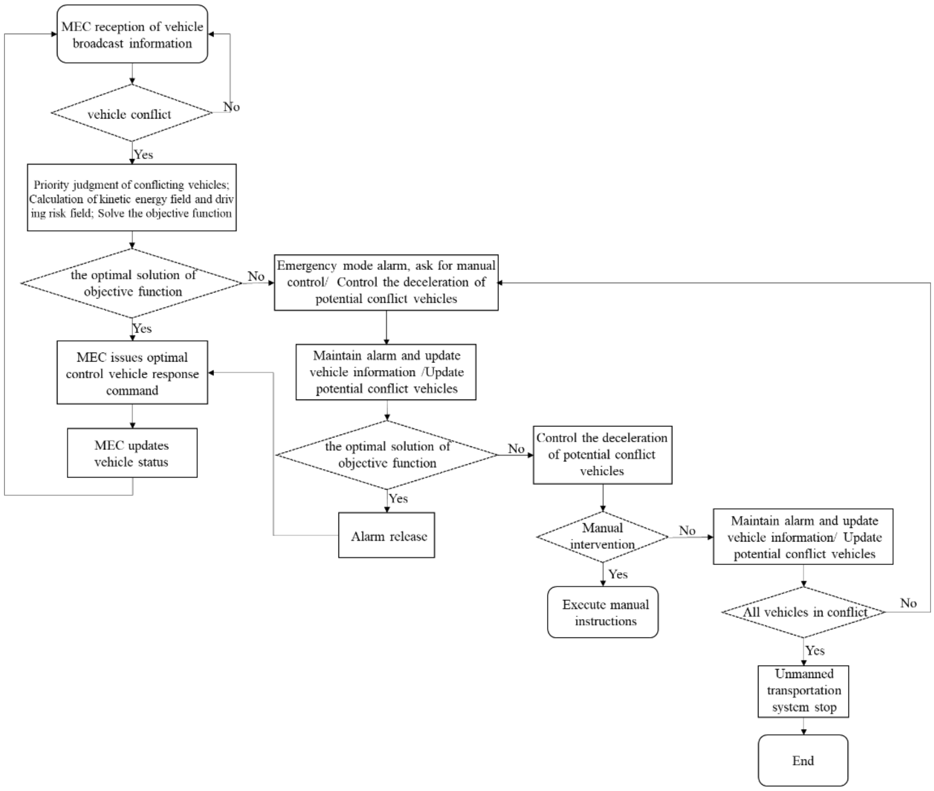


Fig. 3. Flow chart of conflict detection and deconfliction algorithm for intelligent networked mining trucks

4. Simulation and analysis

The functions of the traffic safety auxiliary decision-making system were tested and verified, and a co-simulation platform was built based on PreScan and Simulink. The influence of environmental factors is introduced to verify the adaptability of the access control system to the special environmental conditions of the open-pit mining area.

It was built that a cross-type two-way two-lane intersection without signal intersection road environment, and the road width, right turning radius and Left turning radius are 27m,60m and 70m respectively. The size of the vehicle model, width, length and height are 7m, 11m and 6m respectively, according to the general size of the large mining truck. The planning speed of trucks traveling on different road sections is set based on relevant standards, which includes that the speed of trunk roads is 40km/h, the speed of branch roads is 35km/h, and the speed limit at intersections is 20km/h. The acceleration is around $0.4 \sim 0.6\ \mathrm{m/s^2}$ when it switches between in different roads.

The road environment and traffic scene as shown in Fig. 4 is arranged. The weather condition is set to 1, the dust concentration is set to 0.2, the truck 1 is set to load state and the truck 2 is set to no-load state, and the traffic scene in which the truck 1 takes precedence over the truck 2 is constructed.Simulation tests for conflict resolution of truck 1 and truck 2 without access to road quality sensor and access were conducted respectively, and the results were shown in Fig. 5.

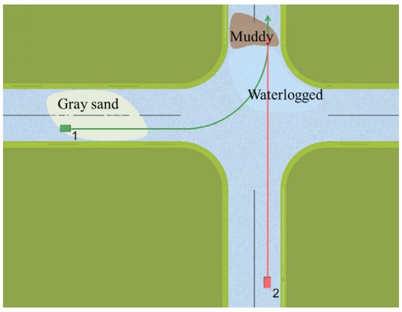
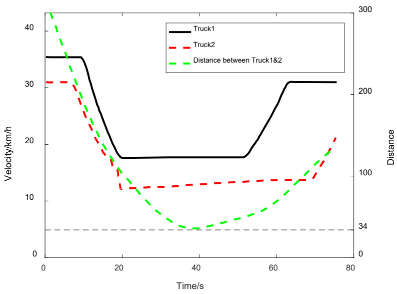


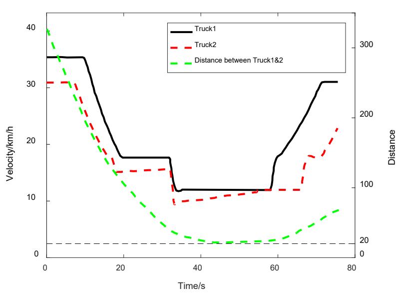
Fig.4 Environmental factors affect the test scenario

As can be seen from the simulation test results, truck 1 passes through the gray sand road firstly. Because the weather conditions are good and the dust concentration is low, the constraint factor given by the fuzzy reasoning module does not change until truck 1 reaches the waterlogged area around 33s, when the constraint factor drops to about 0.6 and the corresponding maximum vehicle speed also decreases, as shown in Fig. 5(b). When the speed of truck1 changes, truck 2, as the control target, decelerates in time to maintain the safe distance between the two vehicles in the potential conflict. At this time, a large acceleration, about $-1.7\,\mathrm{m/s^2}$, is generated, but it is still within the maximum acceleration range under the influence of constraint factors.

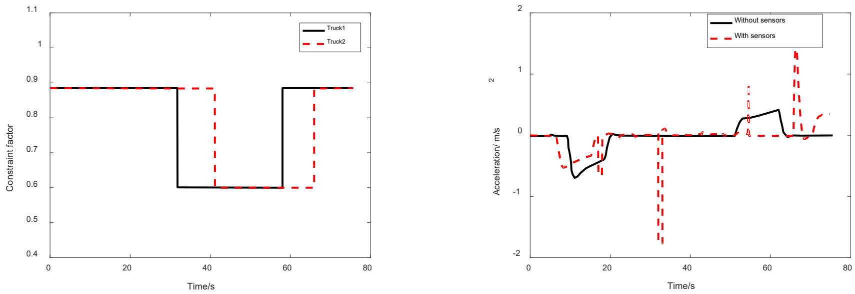
Besides, truck 2 also entered the waterlogged area, but the speed of truck 2 was lower than the maximum speed under the constraint factor. Therefore, there was no obvious change and the minimum distance between the two trucks was about 20m.



(a) Results of tests without access to road surface quality sensors



(b) Results of the test of access to road quality sensors



(c) Change of constraint factor after connecting to road surface quality sensor

(d) Acceleration Comparison

Fig. 5 Results of the test of the overall control system subjected to environmental factors

6. Conclusions

(1) By analyzing the conflict characteristics of unmanned vehicles in mining areas, a circular collision detection model based on safety margin was established, which could effectively predict the possible conflict situation of vehicles combined with the current driving state of vehicles. For vehicles with potential conflicts, a multi-level right-of-way decision-making process adapted to the conflict detection process and related regulations of open-pit mine transportation was designed, which can form right-of-way priority decision-making to ensure transportation efficiency under the premise of compliance and provide a basis for conflict resolution.

(2) The driving risk field theory is introduced, which redefines the sources of the equivalent mass, potential energy field and behavior field generated by the second type of stationary object, and it builds a driving risk field model suitable for the unmanned transportation environment of open-pit mines.

(3) Aiming at the problem of conflict at the unsignalized intersection of open pit mine, the collaborative control algorithm of traffic risk minimization based on model predictive control optimization was designed. The control system can effectively predict potential conflicts within a driving distance of more than 100m, form a reasonable right-of-way decision and resolve conflicts, and ensure that the minimum distance of vehicles with potential conflicts is greater than the set safety value during the process of crossing the intersection.

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