A Model of Airport Emergency Rescue Path Planning Based on Hierarchical Optimized Dijkstra Algorithm

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Abstract
This paper proposed an airport emergency rescue path planning model based on hierarchical optimized Dijkstra algorithm. Firstly, irrotational wave which comes from the traffic wave theory was used to analyze the travel time in crowded intersection, and BPR model was introduced at the same time. Because of the influence of traffic flow to driving time, we analyzed the cases and established the road barrier function theoretical mode on non-congested road based on the BPR model. Then we build the traffic network model to meet the needs of airport’s emergency rescue route planning. The Dijkstra algorithm was improved so that the algorithm program responds the veer of arcs first, instead of nodes. Finally, analog simulation experiment results shows that, the improved Dijkstra algorithm proposed in the paper is more efficient rather than the standard Dijkstra algorithm in case of congestion.

Key words: Hierarchical Optimize, BPR Model, Traffic Wave Theory, Emergency Rescue, Path Planning, Improved Dijkstra Algorithm.

1. INTRODUCTION
When the emergency accidents happen in airport, rapid and effective rescue operation will be the most important measure which can resist disasters and mitigate the spread speed of the harmful consequences (Iannoni and Morabito, 2009). The establishment of an effective airport emergency rescue system is important to the normal operation to airport. When the emergency accident happens in the airport, it is significant that the decisively disposal to reduce the casualties and property loss through path guidance and relief resources scheduling (Liu and Shi, 2002).

Through the reference collection of literature review and Internet network resources, we find that scholars and experts focus the attention on airport emergency analysis, flight planning, and organize optimization, rescue drills, the rescuer training and equipment improvement and so on. Abeyratne (Abeyratne, 2012) pointed out some potential problems and coordination solutions through the in-depth study about rescue work program of aircraft accident. On the other hand, rescue work process itself was lack of depth analysis, and we need to make clear about the bottlenecks and improve it to increase the efficiency of the rescue. Through the emergency research about how to make the accident rescue plan, The experts (Barbash and Ruskin, 2011) proposed the conclusion that how to quickly estimate the number of casualties and take them to hospital as soon as possible is the key point in the process of rescue. Tzeng(Tzeng and Chen, 1999) considering airport’s level and configuration element, and then analyzed the airport fire resource distribution problem. Lord (Lord, 2013) provided a framework to the United States’ comprehensive emergency processing system, and classified the solving role of different department in government when dealing with emergencies and disasters. Besides, they discussed the way to prevent and reduce disasters from happening again, and how emergency response after the disaster was also taken in. Cohn.Campbell (Cohn.Campbell, 1971) analyzed different type of airports’ datas to study service facilities come from different sectors; then they proposed minimum requirements for the number of different resources, including the smallest number of vehicles, rescue response time and rescue personnel and other relevant factors. SyiSu (SyiSu, 2003) set up EMS model with a computer simulation system which can classify rescuers and hospitals into different levels. And then the system will reducing the response time of the rescue, making smoother rescue operations and higher efficiency by using optimized match between rescuer and hospital, respectively, ALS and BLS which can be applied to different levels of aid in the rescue process. Luo Fan (Luo and She, 2002) described airport emergency warning management based on the questionnaire survey.
Moreover, they proposed the airport emergency warning indicator system and analyzed Chinese civil airport existing organizational structure. Chi Wenxue (Chi and Sun, 2005) combined with GIS to did the study of aviation emergency rescue and aid decision support system, and the main function modules of the system was divided into: accident confirmation module, the rescue plan formulation module, the rescue plan modification module, the rescue plan sending module, archiving, summarize and analyze module.

With the weakness of standard Dijkstra algorithm in path planning, the paper proposed an airport emergency rescue route model based on hierarchical optimized Dijkstra algorithm. And furthermore, the study also did the instance simulation to verify the validity of the model.

2. THE JOURNEY TIME CALCULATION MODEL BASED ON HIERARCHICAL RESCUE ROUTE

2.1. The Composition of Journey Time

The journey time is determined by the journey length and vehicle speed on road, so that the first factor of journey time’s calculation is length. When the traffic is fluent, the length of road is the journey length; On the other hand, when the traffic jam happened, vehicles will form queuing phenomenon, and it is due to the downstream intersection congestion. When meet this case, we should measure the queue length of the vehicle first, and the journey length can be calculated with the subtraction between road length and queue length. As the figure 1. Shows, we can divided driving length into two sections : \( a = (A, B) \), \( a_1 = (A, M) \), \( a_2 = (M, B) \), the direction of arrow is the direction of vehicle driving.

![Figure 1. Link travel time chart](image)

In figure 1, point \( A \) is road entrance, point \( B \) is the exports, point \( M \) represents the end of the queue. The length of \( a_1 \) represent the driving length on road \( a \); and the length \( a_2 \) means the queue length because of intersection congestion. If the traffic is fluent, point \( M \) and \( B \) is the same point, and \( a_2 = 0 \), \( a_1 = a \).

\( T_a(t) \) represents the journey time which begin from point \( A \). According to the analysis above, we get the following formula:

\[
L_a = L_f(t) + L_{a_1}[t + w_a(t)] \\
T_a(t) = w_a(t) + d_a[t + w_a(t)]
\]  

(1)  
(2)

In the formula, \( L_a \) : the road length of \( a \); \( L_f(t) \) : the driving length on \( a_1 \) noncongested road; \( w_a(t) \) : time spented on \( a_1 \) road starting from second \( t \); \( L_{a_1}[t + w_a(t)] \) : the queue length of \( a_2 \) road; \( d_a[t + w_a(t)] \) : time spented on \( a_2 \) road starting from second \( t + w_a(t) \)

In generally, shorter distance of road, shorter driving time on \( a_1 \). So we simplified the formula \( L_{a_1}[t + w_a(t)] \) and \( d_a[t + w_a(t)] \) to \( L_a(t) \) and \( d_a(t) \), then the formula transformed as follows:

\[
L_a = L_f(t) + L_a(t) \\
T_a(t) = w_a(t) + d_a(t)
\]  

(3)  
(4)

Urban road network information is typically refreshed at set intervals, the information system see the vehicles on the road, driving in and out vehicle’s number per unit time as a fixed data. The whole time is divided into small units, it means that the journey time is processed in discretization, so it can be turned into discrete function. Set time interval \( \Delta k = [k, k+1) \), \( k \) represent a moment, so we can calculate vehicle’s driving time during \( \Delta k \). So, the driving time on road \( a \) can be expressed as: \( T_a(k) = w_a(k) + d_a(k) \) ; and when the road is out of congestion, \( d_a(k + w_a(k)) = 0 \).
The reason of vehicle’s queue is always because traffic jam in the intersection in downstream. So we try to set up the queuing model in the intersection.

2.2. Driving Time Analysis in Crowded Intersection

Vehicles stopped when meet red traffic lights in road, and then follow-up vehicle queued in high density alignment; And when the green lights turned up, vehicles were launched, so the queue density decreased. The whole process is similar to water and constantly backward propagate with obvious traffic flow wave characteristic.

According to the related research about static traffic distribution, we described the traffic flow wave speed in intersection as:

\[ w_{\text{stop}} = -v_f \eta_j \]

In the formula: \( w_{\text{stop}} \) is parking traffic flow’s wave velocity; \( k_j \) is traffic jam density, it represents the density when all vehicles can’t exercise; \( v_f \) is defined as the speed of free stream; \( k \) is defined as traffic density of upstream to signal intersection;

On red light period \( r \), and parking wave propagation distance to upstream is \( w_{\text{stop}} \cdot r \), so the number of stopped vehicle for the reason is:

\[ N_r = w_{\text{stop}} \cdot r \cdot k_j = v_f \cdot k \cdot r \]

Under dynamic conditions with time factor, the number of stopped vehicle in intersection on \( t \) moment can be defined as:

\[ N_a(t) = v_{f,a} \cdot k_{a,j} \cdot r_a \]

In formula above, \( N_{a,j} \) is the queued vehicle number in red traffic light period \( r \) in intersection downstream of road \( a \) on \( t \) minute; \( k_{a,j} \) is defined as the traffic flow density in road \( a \) on \( t \) minute; \( v_{f,a} \) is the free flow speed in road \( a \); \( r_a \) is the red traffic lighted time in intersection downstream of road \( a \).

And because \( k_{a,j} = \frac{x_{a,j}}{L_a \cdot n} \) (\( x_{a,j} \): traffic loading on road \( a \) at \( t \) minute; \( L_a \):length of road; \( n \): number of road lane), the formula 7 can transfered to:

\[ N_{a,t} = v_{f,a} \cdot \frac{x_{a,t}}{L_a \cdot n} \cdot r_a \]

By discretizing the formula, the vehicle number of intersection at \( t \) and \( t + \Delta t \) minute is:

\[ N_a(t) = v_{f,a} \cdot \frac{x_{a,t}}{L_a \cdot n} \cdot r_a \]

\[ N_a(t + \Delta t) = v_{f,a} \cdot \frac{x_a(t + \Delta t)}{L_a \cdot n} \cdot r_a \]

So the number of vehicle in queue in average during \( \Delta t \) period is:

\[ \frac{N_a(t) + N_a(t + \Delta t)}{2} = \frac{1}{2} \cdot v_{f,a} \cdot \frac{r_a}{L_a \cdot n} \cdot [x_a(t) + x_a(t + \Delta t)] \]

Defined \( S_a \) as an average space length of vehicles on road, so the queue length during \( \Delta t \) period should be:

\[ L_a(t) = \frac{1}{2} \cdot v_{f,a} \cdot \frac{r_a}{L_a \cdot n} \cdot [x_a(t) + x_a(t + \Delta t)] \cdot S_a \]

2.3. Driving Time Analysis in Noncongested Intersection

The noncongested road’s driving time is not only related to the length of the road, the vehicle speed, the detailed information of road is also make the influence to it. Studies generally describe the driving time by road
impedance function. What is called road impedance function refers to the functional relationship between driving time and road traffic load. In the dynamic traffic assignment, we introduced the model of BPR:

\[ t(q) = t_0[1 + \alpha(q/c)^\beta] \]  

(13)

In the formula 13, \( t(q) \) is defined as driving time on \( q \) minute; \( t_0 \) is defined as free flow driving time on road; \( c \) is defined as theory traffic capacity on road; \( q \) is defined as actual traffic flow on road; \( \alpha, \beta \) is regression coefficient; and the typical value is 0.15 and 4.

The model discussed above is simple and easy to apply, but it just considered the effect of traffic flow to road driving time. In this paper, we established the road impedance function’s theoretical model based on BPR model and actual analysis.

The operation of traffic flow on road can be divided into three types: free traffic flow, normal traffic flow and saturated traffic flow. The relationship between vehicle speed and traffic density can be described by figure 2.

The vehicle speed and traffic density will not form a complete linear relationship under normal traffic flow in actual. Considering the influence of other factors and previous research achievement, we adopt Greenberg model as follows:

\[ v = v_n \ln \frac{k}{k_j} \]  

(14)

In formula 14, \( v_n \) is the vehicle speed of largest traffic flow, what is also called critical speed; \( k_j \) is jam density. But when the traffic density is low enough, the speed turned out from formula will varys as the lower of density, so the formula does not applicable in this case. Actually, when traffic density is lower enough, the vehicle speed is basically keep in a stable data which is the fastest speed under the designed condition.

So, we improved Greenberg model:

\[
\begin{align*}
  v &= v_n \ln \frac{k}{k_j}, k > \frac{k_j}{e^2} \\
  v &= v_j, k \leq \frac{k_j}{e^2}
\end{align*}
\]  

(15)

The improved diagram \( v - k \) is demonstrated as figure 3 as follows:
As can be seen from figure 3, the improved model can basically reflect the actual condition of the traffic. When the traffic density is lower, the vehicles can drive at maximum speed; nevertheless, when the traffic density exceeds a certain value, the speed will decrease gradually with the increase of density. If the traffic density increases to a highway, the vehicle speed will drop to a very low level, and basically maintain at a lower value.

Under dynamic condition, the vehicle speed in a period can be discretized as the following formula:

\[
\begin{align*}
v_c(t) &= v_n \ln \left(\frac{k_j}{k_i(t)}\right) > \frac{k_j}{e^2} \\
v_v(t) &= v_j, k_i(t) \leq \frac{k_j}{e^2}
\end{align*}
\]

(16)

In the formula, the relationship between the designed speed, road grade, and lane number is as shown in Table 1.

| Road grade          | Design speed | Unidirectional motor vehicle lane |
|---------------------|--------------|----------------------------------|
| Expressway          | 60-80        | 2-4                              |
| The main road       | 40-60        | 2-4                              |
| Secondary roads     | 30-40        | 1-3                              |
| Branch              | 20-30        | 1-2                              |

3. EMERGENCY ROUTE PLANNING MODEL BASE ON DIJKSTRA'S ALGORITHM

3.1. Network Architecture Model Setting

The shortest time of emergency vehicle’s route is essentially finding the shortest path from emergency station to accident site. Considering the intersection, we can combine with intersection and road section and abstract the road network to an undirected graph form: \( G = (N,D,W,A) \), if no loops in the network diagram.

Thereinto, \( N = \{c_i | \ i = 1,2,...,n\} \) is road node set; represents the delay in node \( j \), when vehicle begins in node \( i \) come through node \( j \) and arrived node \( k \). \( W = w(i,j) \) represents consideration from node \( c_i \) to node \( c_j \). And the actual situation is related to road length, road section capacity, and traffic condition at different time. \( A \subseteq V \times V \) is a set arc. And \( r(i,j) = \{< c_i,c_j , w(c_i,c_j), d_{ij} > \} \) which means every section has three properties: road section is an ordered sequence of nodes; road section’s weight value is time; the driving direction of vehicle.

The model can reflect the driving direction and the delay in intersection. Therefore, when weight value of road section is known, emergency vehicle’s shortest path problem is the issue of minimum weight value between two specified points.

3.2. Hierarchical Optimization of Dijkstra Algorithm

Standard Dijkstra’s algorithm uses binary relation to describe the node situation, because the subsequent node selection is only depends on the linked node in front. However, when the turning delay happens, subsequent node is also related to precursor point of node in front. So, if we want to use the algorithm into the intersection delay situation, we need to increase the intersection’s direction information. But the expression and calculation is also difficult.

In this paper, the Dijkstra algorithm was improved so that the algorithm program responds the vein of arcs first, instead of nodes. In the process of search, some nodes maybe appeared repeatedly, but arc segment won’t. For the convenience of expression, we add some variable definition and symbols as follows:

- \( S \) : set collection, means the optimal path arc segment which has been obtained;
- \( r_0 \) : Virtual edge, the ending point is the starting point \( s \);
- \( P_r \) : Virtual variable, which used to store optimal path’s node sequence \( r \) from starting point to one node.
- \( w(s,j) \) : The weight value from node \( s \) to node \( j \);
- \( l(r) \) : tentative label of \( r \) arc segment;
- \( h(r) \) : the first node of \( r \) arc segment;
- \( f(r) \) : the last node of \( r \) arc segment;
- \( p(r) \) : precursory arc of \( r \) arc segment;
- \( d(r) \) : the optimal path’s length from starting point to arc \( r \) until to the end of \( r \), which means \( d(r_0) = 0 \);
The specific calculation steps are described as follows:

1. **Initialization:** Let's define \( l(r_0) = d(r_0) = 0 \), with arc \( r_0 \) put into arc \( S \), and made other arcs except \( r_0 \) as following: \( l(r) = \infty, r \in A - S \).

2. In order to find \( l(r) = l(r_0) + w(s, i) \), we labeled all the arc segments starting from \( s \) tentatively, and then determined \( l(r) = \min(l(r)) \). So we got \( d(r), \) perpetual label of arc \( r \), and after put arc \( r \) into \( S \), we got the results: \( h(r) = s, f(r) = i, P = (s, f(r)) \).

3. We labeled all the arcs tentatively which started from the ending point of arc \( r \). Firstly, we'll judge the intersection’s direction based on arc \( r \) and other arcs’ trending, it’s may be left, or right, or go straight. We defined \( P(r) = r \) to got \( l(r) \); and defined \( d(r) = \min\{l(r)\} \), at last, put arc \( r \) into \( S \).

4. If \( A = S \), then turn to step (5), or it will turn to (3).

4. INSTANCE ANALYSIS

In order to verify the property of the improved model proposed in the paper, we made the simulated experiment. At first, we took a civil airport as an example, and tested the path planning issue under noncongested condition. Partly abstract roads’ network diagram is shown as figure 4, and both the standard and improved Dijkstra’s algorithm’s path planning results are shown in figure 5.

![Figure 4](image1.png)

**Figure 4.** Road network congestion is not the case of FIG.

![Figure 5](image2.png)

**Figure 5.** Two algorithms path planning results
Then we tested the path planning issue under congested condition and the abstract roads’ network diagram is shown as figure 6. Both the standard and improved Dijkstra’s algorithm’s path planning results are shown in figure 7.

![Figure 6. FIG road network in case of congestion](image)

![Figure 7. Two algorithms path planning results](image)

As can be seen from the above results, the improved Dijkstra’s algorithm is more effective than standard Dijkstr’s algorithm in path planning under the congestion situation and it is conductive to airport’s emergency rescue.

5. CONCLUSION

Safety is the primary problem in airport industry. Once the civil aviation accidents occured, how to organize rescue timely and efficiently is an important research direction in the field of aviation security. The paper aimed at the defects of standard Dijkstra’s algorithm in path planning, and proposed an civil aiport’s emergency rescue path planning model based on hierarchical optimized Dijkstra algorithm. And the improved Dijkstra’s algorithm is more effective than standard Dijkstr’s algorithm in path planning under the congestion situation.

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