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Decision model and algorithm for traffic rescue resource dispatching on expressway

Chai Gan Zhu Canghui Wan Shui Pu Juyi

(Intelligent Transportation System Research Center, Southeast University, Nanjing 210096, China)

Abstract: In order to solve the problems of potential incident rescue on expressway networks, the opportunity cost-based method is used to establish a resource dispatch decision model. The model aims to dispatch the rescue resources from the regional road networks and to obtain the location of the rescue depots and the numbers of service vehicles assigned for the potential incidents. Due to the computational complexity of the decision model, a scene decomposition algorithm is proposed. The algorithm decomposes the dispatch problem from various kinds of resources to a single resource, and determines the original scene of rescue resources based on the rescue requirements and the resource matrix. Finally, a convenient optimal dispatch scheme is obtained by decomposing each original scene and simplifying the objective function. To illustrate the application of the decision model and the algorithm, a case of the expressway network is studied on areas around Nanjing city in China and the results show that the model used and the algorithm proposed are appropriate.

Key words: dispatch decision model; scene decomposition algorithm; traffic rescue resource; expressway

The disruption by incidents on expressways is overwhelming the common highways[1]. The total delay caused by an incident consists of detection time, dispatch time, travel time and clearance time[2]. Dispatch decision time is composed of dispatch time and travel time. The decision model in this paper describes the selected rescue depots, the kinds and numbers of assigned service vehicles, and the algorithm decides dispatch strategies by solving the decision model.

Considering any current incident, the rescue decision is to dispatch the closest available vehicles, and Yamada[3] transformed this dispatch problem into the shortest path of the network. Considering both current and potential incidents, a mixed-integer programming model with probabilistic constraints was proposed by Ozbay et al.[4]. Considering the kinds of rescue resources, the multi-commodity and multi-modal network flow model was put forward by Haghani et al.[5]. Targeting the purposes of rescue decisions, researchers have concentrated on minimum dispatch time. Ozbay et al.[6] used the Arena simulation package to evaluate the performance of incident management operations. Domestic researches were just starting. Fuzzy programming in selection of multi-depots for emergency systems was proposed by Liu et al.[7-8]. However, previous studies on the dispatch problem have failed to consider the methods and practices in response to multiple incidents, especially, the decision model and the algorithm for traffic rescue resource dispatch on expressways. The objective of this paper is to provide an adaptive model and propose an appropriate algorithm for making decisions related to the depots selected and the kinds and numbers of service vehicles assigned. The research findings can be effectively incorporated into a traffic rescue resource dispatch decision support system on expressways.

1 Dispatch Decision Model

1.1 Modeling approach

In view of traffic rescue on expressways, dispatch strategies in response to low levels of incidents are made by considering direct costs[9], namely, dispatch the service vehicles from the depot closest to the incidents. In response to high levels of incidents, rescue resources from the local road networks are needed to dispatch, so the opportunity cost method is introduced to build the dispatch decision model. The basic idea of the method is that resources are alternatively utilized. Every kind of resource is of considerable use, and once a resource is put into one application, it will not be available for another use. On the premise of no additional rescue resources, the method not only takes the current incident rescue costs into account, but also gives consideration to potential incident rescue costs. It is suitable for dispatching rescue resources on expressway networks.

1.2 Opportunity cost-based model

The direct costs caused by a current incident rescue is defined as $\sum_{i\in L}\sum_{f\in F}\lambda_{if}x_{if}$ [9]. λ_{if} is the minimum dispatch decision time for a vehicle from depot $i\in L$ to the current incident $f\in F$ (L is a set of depot nodes, $|L|=l$, and each depot node i provides r_i vehicles. F is a set of current incident nodes, $|F|=m$, and each current incident node f requires n_f vehicles). x_{if} is the number of vehicles dispatched from i to f. In the process of assigning the closest vehicle to serve the current incident, once an additional incident occurs in node v, vehicles in the closest depot will not be available to serve the new incident. Note P_v is the probability of a potential incident occurring at any node v ($v\in N$, N is a set of nodes in the road network), so the opportunity cost caused by the potential incident is defined as $\sum_{i\in L}\sum_{v\in N}P_v(\lambda_{iv}-\lambda_v)y_{iv}$ [10]. In general, the occurrence of incidents follows a Poisson distribution, so only one additional incident could occur simultaneously. λ_{iv} is the minimum dispatch decision time for a vehicle from depot i to potential incident node v, and λ_v means the minimum dispatch decision time for a vehicle from all

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Biography: Chai Gan (1963—), male, doctor, associate professor, chaig@263.net.

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depots to $v(\lambda_v = \min\{\lambda_{iv}\}$, for all $v \in N)$. If a vehicle is dispatched from i to v in response to an additional incident, $y_{iv} = 1$, otherwise $y_{iv} = 0$. x represents an arbitrary x_{if}, and y represents an arbitrary y_{iv}. s_i is the remaining available vehicles dispatched by a potential incident after rescuing a current incident. So, the opportunity cost-based model is stated as follows:

$$\min\Big[\sum_{i\in L}\sum_{f\in F}\lambda_{if}x_{if} + \sum_{i\in L}\sum_{v\in N}P_v(\lambda_{iv} - \lambda_v)y_{iv}\Big] \quad (1)$$

$$\text{s. t.} \quad \sum_{f\in F}x_{if} + s_i = r_i \qquad \forall\, i \in L; s_i \geqslant 0 \quad (2)$$

$$\sum_{i\in L}x_{if} = n_f \qquad \forall f \in F \quad (3)$$

$$\sum_{i\in L}y_{iv} = 1 \qquad \forall\, v \in N \quad (4)$$

$$y_{iv} \leqslant s_i \qquad \forall\, i \in L; v \in N \quad (5)$$

$$x \geqslant 0 \text{ (and integer)}, y \text{ binary} \quad (6)$$

The objective function denotes that the dispatch decision is to minimize the total costs. They include the direct and the opportunity costs derived from the current and potential incidents. Eq. (2) ensures that the number of vehicles dispatched from any depot must not exceed the number of service vehicles available at the depot. Eq. (3) stipulates that the number of vehicles dispatched to any current incident node should meet the service vehicle requirements at that node. Eq. (4) requires a service vehicle to be ready for dispatch in order to provide rescue resources to potential incident at any node in the network, whereas Eq. (5) states that such an additional vehicle in Eq. (4) can be dispatched from a depot only if it is available at that depot. Eq. (6) imposes integrality and binary restrictions on the decision variables.

2 Scene Decomposition Algorithm

The opportunity cost-based model is a mixed-integer programming model. The computation using the general branch-and-bound approach increases exponentially with variable dimensions, and more nodes, more branches. The scene describes a series of facts analyzing possible future events by considering alternative outcomes. The decision model takes the potential incident into consideration, so a scene decomposition algorithm is proposed to solve the model and decrease the computation. The scene decomposition algorithm consists of the following steps:

Step 1 Formation of the resource scene

The resource matrix $\boldsymbol{R}_{m\times n}$ is derived from m depots providing n kinds of rescue resources on expressways, such as police patrol vehicles, administration vehicles, wreckers, cranes, ambulances and fire engines. The arbitrary element r_{ij} in $\boldsymbol{R}_{m\times n}$ means the number of the j-th kind of service vehicles provided by the i-th depot. U is a set of $u(u \leqslant n)$ kinds of vehicles determined by the current incident levels, so the resource scene $\boldsymbol{R}_{m\times u}$ is a matrix by selecting u columns from $\boldsymbol{R}_{m\times n}$.

$$\boldsymbol{R}_{m\times u} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1u} \\ r_{21} & r_{22} & \cdots & r_{2u} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mu} \end{bmatrix} \quad (7)$$

Step 2 Formation of the original scene and the initial decomposed scene

For required numbers p from the q-th ($q \in U$) kinds of rescue resources, it is necessary to decide which depots can provide such service vehicles. Hence, taking elements from the q-th column of $\boldsymbol{R}_{m\times u}$, the original scene $\boldsymbol{R}_1 = \{r_{1q}, r_{2q}, \ldots, r_{mq}\}$ is formed. The initial decomposed scene $\boldsymbol{R}_1^*$ is obtained by

$$\boldsymbol{R}_1^* = \{r_{1q}^1, r_{2q}^1, \ldots, r_{mq}^1\}$$
$$r_{iq}^1 = \begin{cases} 1 & r_{iq} > 0 \\ 0 & r_{iq} = 0 \end{cases} \qquad i = 1, 2, \ldots, m \quad (8)$$

Step 3 Formation of the first dispatch scheme

Let the first dispatch scheme be $\boldsymbol{X}_1 = \{x_{1q}, x_{2q}, \ldots, x_{mq}\}$. If the first vehicle of the q-th kind is provided by depot i, $x_{iq} = 1$ and others are zero. For the sake of $\boldsymbol{X}_1$, the assumptions made above are that different kinds of service vehicles dispatched for the same incident are independent of each other; a single vehicle is required to rescue one current incident that has occurred, and every depot has one service vehicle. According to the hypothesis, Eq. (3) can be changed into $\sum_{i\in L}x_{if} = 1$, $\forall f \in F$. Suppose that $f_0 \in F$ is the node at which the current incident occurs and $i_0 \in L$ is the depot from which the vehicles are dispatched, then $\sum_{i\in L}\sum_{f\in F}\lambda_{if}x_{if} = \sum_{i\in L}\lambda_{if_0}x_{if_0} = \lambda_{i_0f_0}$. The vehicle from depot i_0 has been dispatched to provide rescue services to the current incident and if serving the additional incident v, other depots needs to be selected. As a result, Eq. (4) can be transformed into $\sum_{w\in L-\{i_0\}}y_{wv} = 1$, $\forall\, v \in N$. Denote $\lambda_{v|i_0}$ as the minimum time for a vehicle dispatched from any depot except i_0 to potential incident node v, so the opportunity cost is $\sum_{i\in L}\sum_{v\in N}P_v(\lambda_{iv} - \lambda_v)y_{iv} = \sum_{w\in L-\{i_0\}}\sum_{v\in N}P_v(\lambda_{wv} - \lambda_v)y_{wv} = \sum_{v\in N, w\in L-\{i_0\}}P_v(\lambda_{wv} - \lambda_v) = \sum_{v\in N}P_v(\lambda_{v|i_0} - \lambda_v)$. The objective function(1) is simplified as

$$\min\Big\{\lambda_{i_0f_0} + \sum_{v\in N}P_v(\lambda_{v|i_0} - \lambda_v)\Big\} \quad (9)$$

Due to the elements whose values are 1 in $\boldsymbol{R}_1^*$, it is necessary to determine which depots that can provide the q-th kind of resources and induce the corresponding parameters $\lambda_{i_0f_0}, \lambda_{v|i_0}, \lambda_v$ into calculating Eq. (9). If the depot i satisfies the simplified objective function, let $x_{iq} = 1$, and we obtain X_1.

Step 4 Formation of the process of scene decomposition

If $p \geqslant 2$, the second vehicle of the q-th kind is needed to be dispatched and the scene continues to be decomposed. After obtaining the first dispatch scheme, the next scene becomes

$$\boldsymbol{R}_2 = \boldsymbol{R}_1 - \boldsymbol{X}_1 = \{r_{1q} - x_{1q}, \ldots, r_{iq} - x_{iq}, \ldots, r_{mq} - x_{mq}\} \quad (10)$$

And the corresponding second decomposed scene is described as

$$\boldsymbol{R}_2^* = \{r_{1q}^2, r_{2q}^2, \ldots, r_{mq}^2\}$$
$$r_{iq}^2 = \begin{cases} 1 & r_{iq} - x_{iq} > 0 \\ 0 & r_{iq} - x_{iq} = 0 \end{cases} \qquad i = 1, 2, \ldots, m \quad (11)$$

For the q-th kind of rescue resources, the second dispatch scheme $\boldsymbol{X}_2$ denotes that the second vehicle required is provided by another depot. The approaches of obtaining each dispatch scheme are identical, so $\boldsymbol{X}_2$ is also obtained by calculating Eq. (9).

With the decomposed scenes $\boldsymbol{R}_k^*$ ($k = 1, 2, \dots, p$) getting $\boldsymbol{X}_k$, the process of scene decomposition is

$$\boldsymbol{R}_1 \to \boldsymbol{R}_1^* \to \boldsymbol{X}_1 \Rightarrow \boldsymbol{R}_2 \to \boldsymbol{R}_2^* \to \boldsymbol{X}_2 \Rightarrow \dots \Rightarrow \boldsymbol{R}_p \to \boldsymbol{R}_p^* \to \boldsymbol{X}_p \quad (12)$$

Step 5 Formation of the dispatch results

The series $\boldsymbol{X}_1, \boldsymbol{X}_2, \dots, \boldsymbol{X}_p$ constitute dispatch results of the q-th kind of rescue resources. In the same way, the dispatch results of u kinds of service vehicles required by incidents are obtained.

3 A Case Study on Expressway Network

Take the expressway network around Nanjing city for example. Hubs, interchanges and tollgates are all set nodes in the road network. The service vehicles travel U-turn or in upper and lower directions, so the arcs between hubs and nodes are bi-directional and the nodes between upper and lower roadways are linked. When rescue vehicles run at a certain speed, dispatch decision time can be replaced by the distance. In this case, the arcs are valued based on the actual distance between two nodes. The evaluation of wreckers and cranes are twice as much as police patrol vehicles and administration vehicles. The expressway network applicable to wrecker and crane evaluation around Nanjing city is shown in Fig. 1. The kinds and numbers of service vehicles allocated in the depots are shown in Tab. 1. The probability of a potential incident occurring at any key node is shown in Tab. 2.

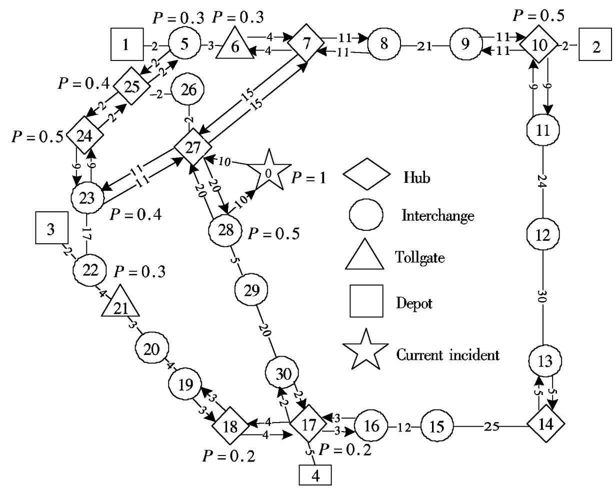

Fig. 1 The expressway network around Nanjing city applicable to the evaluation of wreckers and cranes

Tab. 1 The kinds and numbers of service vehicles in the depots

Number of depots	Location of depots	Expressways	Police patrol vehicles	Administration vehicles	Wreckers				Cranes	
					3 t	8 t	48 t	60 t	40 t	60 t
1	Maqun interchange	Hu-Ning	2	2	1	1	1	1	1	1
2	Zhenjiang interchange	Hu-Ning	2	2	1	1	1	0	1	0
3	Lukou interchange	Airport	2	2	0	1	1	1	1	0
4	Lishui interchange	Ning-Hang	2	2	1	0	1	1	1	1

Tab. 2 The probability of a potential incident occurring at key nodes

Number of nodes	Expressways	Name	P_v
5	Hu-Ning	Maqun	0.3
10		Dantu	0.5
18	Ning-Gao	Luojiabian	0.2
22		Lukou	0.3
23		Cuipingshan	0.4
6	Airport	Main tollgate	0.3
24		Huashenmiao	0.5
25		Gaoqiaomen	0.4
17	Ning-Hang	Guizhuang	0.2
28		Hushu	0.5

The current incident occurs between Hushu and Shangfang interchange on Ning-Hang expressway. The incident node 0 is a ten-minute distance from the Hushu interchange. The requirements of rescue resources are determined by the level of the incident and are shown in Tab. 3.

Based on the steps of the scene decomposition algorithm proposed in this paper, the process of solving the dispatch problem is shown as follows:

Step 1 According to Tab. 1 and Tab. 3, the resource matrix and the resource scene are formed respectively.

Resource matrix

$$\boldsymbol{R}_{4\times 8} = \begin{bmatrix} 2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\ 2 & 2 & 1 & 1 & 1 & 0 & 1 & 0 \\ 2 & 2 & 0 & 1 & 1 & 1 & 1 & 0 \\ 2 & 2 & 1 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}$$

Resource scene

$$\boldsymbol{R}_{4\times 5} = \begin{bmatrix} 2 & 2 & 1 & 1 & 1 \\ 2 & 2 & 1 & 1 & 0 \\ 2 & 2 & 1 & 1 & 0 \\ 2 & 2 & 1 & 1 & 1 \end{bmatrix}$$

Step 2 For the wreckers of 48 t, two service vehicles are needed to be dispatched as seen from Tab. 3. Taking elements from the third column in $\boldsymbol{R}_{4\times 5}$, the original scene is $\boldsymbol{R}_1 = \{1, 1, 1, 1\}$. The initial decomposed scene $\boldsymbol{R}_1^* = \{1, 1, 1, 1\}$ by Eq. (8).

Tab. 3 The kinds of numbers of rescue resources required

Police patrol vehicles	Administration vehicles	Wreckers				Cranes	
		3 t	8 t	48 t	60 t	40 t	60 t
3	2	0	0	2	0	1	1

Step 3 According to Tab. 1, all the depots can provide the wreckers of 48 t for the incident node 0. According to Tab. 2 and Eq. (9), the first dispatch scheme is formed.

$$\lambda_{1\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|1}-\lambda_v)=\lambda_{1\text{-}0}+P_5(\lambda_{5|1}-\lambda_5)+P_6(\lambda_{6|1}-\lambda_6)+P_{10}(\lambda_{10|1}-\lambda_{10})+P_{17}(\lambda_{17|1}-\lambda_{17})+P_{18}(\lambda_{18|1}-\lambda_{18})+P_{22}(\lambda_{22|1}-\lambda_{22})+P_{23}(\lambda_{23|1}-\lambda_{23})+P_{24}(\lambda_{24|1}-\lambda_{24})+P_{25}(\lambda_{25|1}-\lambda_{25})+P_{28}(\lambda_{28|1}-\lambda_{28})=$$
$$38+0.3\times(32-2)+0.3\times(35-5)+0.5\times(2-2)+0.2\times(5-5)+0.2\times(9-9)+0.3\times(2-2)+0.4\times(19-15)+0.5\times(28-6)+0.4\times(30-4)+0.5\times(32-28)=81$$

$$\lambda_{2\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|2}-\lambda_v)=115$$
$$\lambda_{3\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|3}-\lambda_v)=66.3$$
$$\lambda_{4\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|4}-\lambda_v)=46.4$$

$\min\{\lambda_{i_0f_0}+\sum_{v\in N}P_v(\lambda_{v|i_0}-\lambda_v)\}=\min\{81,115,66.3,46.4\}=46.4$. Therefore, one wrecker of 48 t is dispatched from depot 4 to rescue the current incident first, and the first dispatch scheme is $X_1=\{0,0,0,1\}$.

Step 4 $R_2=R_1-X_1=\{1,1,1,0\}$ by Eq. (10), and $R_2^*=\{1,1,1,0\}$ by Eq. (11). Due to the corresponding depots 1, 2, and 3, the elements whose values are 1 in R_2^*, Eq. (9) is calculated as

$$\lambda_{1\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|1}-\lambda_v)=81$$
$$\lambda_{2\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|2}-\lambda_v)=115$$
$$\lambda_{3\text{-}0}+\sum_{v\in N}P_v(\lambda_{v|3}-\lambda_v)=66.3$$

$\min\{\lambda_{i_0f_0}+\sum_{v\in N}P_v(\lambda_{v|i_0}-\lambda_v)\}=\min\{81,115,66.3\}=66.3$. As a result, one wrecker of 48 t is dispatched from depot 3 to serve the current incident secondly, and the second dispatch scheme is $X_2=\{0,0,1,0\}$.

Step 5 For the wreckers of 48T, X_1 and X_2 means the two required vehicles are dispatched from depots 4 and 3 to the current incident. For the remaining four kinds of vehicles, return to step 2; otherwise, stop.

Tab. 4 The dispatch results of rescue resources required

Number of depots	Police patrol vehicles	Administration vehicles	Wreckers				Cranes	
			3 t	8 t	48 t	60 t	40 t	60 t
3	1	0	0	0	1	0	0	0
4	2	2	0	0	1	0	1	1

As can be seen from Fig. 1 and Tab. 4, the results indicate that the dispatch decision time from depots 1 and 4 to current incident node 0 is approximate (the values are 38 and 42), but the location of the current incident and depot 4 are both in Ning-Hang expressway, so service vehicles in depot 4 should be dispatched to assist in the rescue at the incident. As for the potential incident nodes, although the dispatch decision time for vehicles from depot 1 to current incident node 0 is minimum (the value is 38, and others are 90, 60, 42), the total costs of depot 3 are minimum due to the opportunity costs, which demonstrates that dispatching the vehicles from depot 3 is more proper than doing so from depot 1. The dispatch results in the case show that the scene decomposition algorithm is validated in practical applications.

4 Conclusion

Dispatching the rescue resources is of major concern in the engineering practice of traffic rescue on expressway networks. The dispatch decision model built by the opportunity cost-based method is used to determine depot selection and the kinds and numbers of service vehicles for the potential incidents. The scene decomposition algorithm proposed can decrease computational complexity and obtain dispatch results accurately and conveniently. The case study in this paper shows that the decision model and the scene decomposition algorithm are suitable for the engineering practice of traffic rescue resource dispatch on expressway networks.

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高速公路交通救援资源派遣的决策模型与算法

柴 干 朱苍晖 万 水 濮居一

(东南大学智能运输系统研究中心,南京 210096)

摘要:为了解决高速公路路网潜在事故的救援问题,应用机会成本方法建立资源派遣决策模型.该模型能够调度区域路网的救援资源,获得用于潜在事故救援的救援点与救援车辆数.针对模型的计算复杂性,提出情景分解算法.该算法首先将多资源派遣问题分解为各个单资源派遣问题,然后根据救援需求和资源矩阵,确定所需救援资源的原始情景.最后,通过对原始情景的分解和目标函数的简化,便捷获取资源派遣方案.以南京市周边高速公路路网作为应用实例,验证了所用模型与所提算法的可行性.

关键词:派遣决策模型;情景分解算法;交通救援资源;高速公路

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