Selecting the Best Links for Lane-reversal in Wide-area Evacuation Based on the Critical Edge Model of Dynamic Maximum Flow Increase

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Abstract—Based on the theory of dynamic flow, we study the optimization problem of dynamic reverse lane, that is, the selection of the road section and the optimization of the time period of lane reverse operation. We abstract an evacuation road network as a directed network with variable capacity, and define the critical dynamical edge for increasing the dynamical maximum flow value of such network. We can get alternative links and corresponding time period for lane-reversal operation by searching critical dynamical edges for increasing the dynamical maximum flow value. We present a modified algorithm to find such critical dynamical edges on the basis of the maximal capacity path algorithm for the static maximum flow problem. We also give a numerical example and test the effects through traffic simulation. The results show that evacuation time can be effectively decreased through taking dynamical reversal lane scheme in regional evacuation.

1. INTRODUCTION
Lane Reversal, also known as contra-flow, is to increase the traffic capacity of road links and even the whole road network in a certain direction by temporarily changing the traffic direction of some lanes. As a typical measure of evacuation traffic organization, lane reversal has been widely used, such as Hurricane George and Hurricane Floyd evacuation Organization in the United States in the late 1990s, as well as evacuation traffic organizations in Louisiana and Mississippi[1].se components, incorporating the applicable criteria that follow.

There are many research results on the problem of reverse lane in the past, some of which pay attention to the key points of operation and the evaluation of effect from the specific operational level. Litman (2006) analyzed the feasibility of reverse lane under various disasters[2]. Wolson and Lambert (2008) analyzed the conditions and key points of contra-flow on highway section from the aspects of infrastructure, traffic demand, operation method and so on[3]. Wolson (2008) analyzed the actual operation effect of lane reversal based on the traffic flow data during Hurricane Katrina evacuation in Louisiana in 2005[4]. Knapper et al. (2010) analyzed the implementation effect of contra-flow from the point of travelers through questionnaire, in the background of the reverse management of the road near the Gronin Stadium of Netherlands after the last football match[5]. Cova et al. (2003) proposed an improved integer programming model based on the minimum cost flow, which provides a scheme of lane reversl and temporary intersection control during evacuation[6]. Xie and Turnquist deepened the research idea of Cova, proposed a more perfect bilevel programming model, and designed a Tabu
search heuristic algorithm based on Lagrangian relaxation condition\cite{7}. Ren Gang et al. (2015) introduced the concept of network supersaturation, and studied the comprehensive optimization of lane reversal and intersection conflict resolution\cite{8}-\cite{9}.

There are also some studies that pay attention to the choice of lane reversal location from the macro level of the road network. In the case of the highway network, it is mainly the position of the road section from the forward lane to the reverse lane (also known as the additional intersection). For example, Wolfram (2001) discussed some operational problems of contra-flow transition location with respect to the evacuation of the hurricane, and emphasized the route re-allocation at the entrance and exit of the reverse link\cite{10}. Zhou Yafei et al. (2013) used cell transmission model (CTM) to simulate and analyze the different starting positions of reverse lane in highway network\cite{11}. As far as the urban road network is concerned, it is most reasonable to consider the selection of reversal links, that is, which links are selected to expand the capacity by reverse. Ziliaskopoulos (2006) proposed a heuristic algorithm based on simulation allocation and Tabu search for reversal link search in large-scale evacuation road network\cite{12}. Shekhar and Kim (2008) proved that the optimal selection of reversal links in a road network overload, and present the integer programming model suitable for low overload and greedy algorithm suitable for high overload respectively\cite{13}. Wang et al. (2013) considered the preparation time and the priority of evacuation objects, and optimized the selection of reversal links with the goal of the shortest evacuation time and the minimum number of reverse links\cite{14}. Min and Lee et al. (2013) defined the problem of the maximum throughput flow in a network, and gave an algorithm to determine the reversal links of a network by finding the maximum throughput flow\cite{15}. Gao Mingxia (2016) gave a method for optimizing the selection of reversal links for evacuation based on the critical edge model of maximum flow increasing\cite{16}.

Previous studies on reversal lane management have paid much attention to the selection of road links, but the time limit of reverse management is rarely involved. Once the link is selected, it means that the link is subject to reverse management throughout the evacuation period. It is of great practical significance for the implementation of the dynamic reverse Lane scheme and the attention to the time limit of reverse operation when selecting the road section.

We study the problem of dynamical reversal lane based on the DMF (Dynamic Maximum Flow) theory, which is to optimize the choice of links and the time period for lane-reversal operation. We abstract an evacuation road network as a directed network with variable capacity, and define the critical dynamical edge for increasing the dynamical maximum flow value of such network. We get alternative links and corresponding time period for lane-reversal operation by searching critical dynamical edges for increasing the dynamical maximum flow value in such network. We present a modified algorithm to find such critical dynamical edges on the basis of the maximal capacity path algorithm for the static maximum flow problem. We also give a numerical example and test the effects through traffic simulation.

2. PROBLEM DESCRIPTION

2.1. The DMF and the critical edge for flow increasing in the network with variable capacity

The DMF problem, proposed by Ford-Fulkerson\cite{17}, is an extension of the classical static maximum flow problem. Its goal is to transport as many flows from the starting point to the end point in a given time $[0, T]$. In this paper, we define a DMF problem with variable capacity. The time $[0, T]$ of the problem is discretized into $L$ intervals with equal size, and the interval number is represented by $l$. Treating road links as arcs and intersections as nodes, we express the evacuation road network as a network $G=(V, A, C, U)$. $V = \{i/i=1,2,\cdots,n\}$ is the set of nodes(intersections) with $|V|=n$, $A = \{(i,j)/i,j=1,2,\cdots,n\}$ is the set of arcs(links) with $|A|=m$, $C = \{c_{ij}(l)/i,j=1,2,\cdots,n; l=1,2,\cdots,n\}$ is the set of link capacities with $c_{ij}(l)$ indicating the capacity of link $(i,j)$ in the interval $l$. 


is the set of link traveling time with $u_{ij}$ indicating the traveling time of link $(i,j).$ With nodes $1$ and $n$ represent the starting and end point, respectively, $f_{ij}(l)$ representing the flow into the arc $(i,j)$ within the interval $l$ and $v(l)$ representing the total flow arriving at the end node before period $l.$ For any edge $(i,j)$ between the starting and ending point pair $(s, t),$ if the capacity is increased during the period $l,$ that is to say, $c_{ij}(l) = \lambda c_{ij}(l), \lambda > 1,$ the new dynamic maximum flow value is recorded as $v_{G^+}(i,j,l).$ If there exist a dynamic edge $(i^*, j^*, 1^*)$ which can make the formula

$$v_{G^+}(i', j', l') \geq v_{G^+}(i,j,l)$$

established for any dynamic edge $(i,j,l),$ the dynamic edge $(i^*, j^*, 1^*)$ is defined as the critical edge of DMF increase of the network. In other words, the dynamic maximum flow value can be increased to the maximum by expanding the capacity of edge $(i^*, j^*)$ within the period $1^*.$

2.2. The selection of contra-flow links based on the critical edge of DMF increase

The problem of dynamical reversal lane optimization is mainly considered to find the appropriate road links in a road network and expand its capacity through reverse management in the appropriate period of time, so as to improve the overall capacity of evacuation direction. The critical edge DMF increase refers to the dynamic edge (edge and period) which improves the flow value the most after capacity expansion. Although the distribution mode of traffic flow in a road network during evacuation does not necessarily fully accord with the state represented by dynamic maximum flow (DMF), the links and periods corresponding to the critical edge of DMF increase undoubtedly play a key role. By searching for the dynamic key edge and secondary key edge of the DMF in the network, a series of dynamic road links, that is, the road links and the corresponding periods, which play an important role in improving the overall evacuation capacity of the road network, can be obtained.

3. ALGORITHM

According to the definition, to find the dynamic critical edge of the DMF increase, the DMF of the new network after capacity expansion should be considered for every dynamical edge. And then the dynamic critical edge of the DMF increase can be determined by comparing the increased flow value. There are many unnecessary calculations in this natural algorithm. An improved algorithm for finding the dynamic critical edge of DMF increase is given based on the augmenting path algorithm for the DMF problem. The idea of the algorithm is as follows: firstly, the DMF of the initial network is calculated by using the dynamic maximum capacity path algorithm, and the dynamic augmenting paths found are recorded. Then each dynamic edge in the network is judged whether it belongs to one of the dynamic augmenting paths. If the dynamic edge is not included in any augmenting path, it can be concluded as having no effect on the DMF increase, otherwise the DMF of the new network after the expansion of the dynamic edge can be calculated. The DMF of the original network can be used as the initial feasible flow when calculating the DMF in the new network.

The algorithm steps are as follows:

Step1: Let $l = 0.$

Step2: If $l > L,$ the algorithm ends. Otherwise, let $R=A,$ calculate the DMF $f_G(L)$ of the original network, record the flow value as $v_G(L)$ and each augmenting path as $L_1(l),$ $L_2(l),$ $L_3(l),\cdots.$

Step3: If $R = \emptyset,$ go to step 6. Otherwise, taking any $(i, j) \in R,$ find an augmenting path including $(i, j),$ if $(i, j)$ is not included in any augmenting path, go to step 4. Otherwise, go to step 5.

Step4: Taking the maximum flow $f_G(L)$ as the initial feasible flow of network $G^+_{(i,j)}$ (the new network after expanding edge $(i,j)$ in interval $l$), find the maximum flow of the new network $G^+_{(i,j)}$, recording the flow value as $v_{G^+_{(i,j)}}.$ Let $R = R - \{(i,j)\}$ and go to step 3.
Step 5: The expansion of edge \((i,j)\) in interval 1 has no effect on the DMF of network \(G\), let \(R = R - \{(i,j)\}\) and go to step 3.

Step 6: Compare the dynamical maximum flow value of the new network after expansion of each edge and sort in descending order.

Step 7: Let \(l = l + 1\) and go to step 2.

4. Numerical Example

4.1. Initial data
We analyzed our proposed method by taking the evacuation around the petrochemical synthetic rubber plant of Lanzhou city of China as an example. We abstract the evacuation network as a directed network, as shown in figure 1. In figure 1, node 2, 3 represent the source points of evacuation, and node 9, 10, 11, 13 represent the end points of evacuation. For simplicity of calculation, we add virtual starting point 1 and virtual end point 14. The capacity and travel time of the road links are shown in the brackets beside each edge, like (capacity(\(pcu/h\)), time(\(min\))).

![Figure 1. Abstract network corresponding to the evacuation network](image)

4.2. Calculation results
We assume that the period that the problem is located is 60 minutes and discretize it into 60 intervals of 1 minute. We calculate the DMF of the new network after the expansion of some links in different periods as well as the original network by using the algorithm mentioned above and give the results in table 1, in which “F-V” means flow value.

| Net-work F-V time | \(v_g\) | Net-work F-V time | \(v_{G(2,1)}\) | \(v_{G(3,2)}\) | \(v_{G(1,15)}\) | \(v_g\) | \(v_{G(2,1)}\) | \(v_{G(3,2)}\) | \(v_{G(1,15)}\) |
|----------------|--------|-------------------|----------------|----------------|----------------|--------|----------------|----------------|----------------|
| 0               | 0      | 0                 | 0              | 0              | 0              | 31     | 583            | 845            | 844            | 585            |
| 1               | 0      | 0                 | 0              | 0              | 0              | 32     | 604            | 876            | 874            | 606            |
| 2               | 0      | 0                 | 0              | 0              | 0              | 33     | 625            | 907            | 904            | 627            |
| 3               | 9      | 9                 | 18             | 9              | 34             | 646    | 938            | 934            | 648            |
|   | 18 | 18 | 36 | 18 | 35 | 667 | 969 | 964 | 669 |
|---|----|----|----|----|----|-----|-----|-----|-----|
| 5 | 37 | 37 | 64 | 39 | 36 | 688 | 990 | 994 | 690 |
| 6 | 58 | 68 | 94 | 60 | 37 | 709 | 1021| 1024| 711 |
| 7 | 79 | 99 | 124| 81 | 38 | 730 | 1052| 1054| 732 |
| 8 | 100| 130| 154| 102| 39 | 751 | 1083| 1084| 753 |
| 9 | 121| 161| 184| 123| 40 | 772 | 1124| 1114| 774 |
|10 | 142| 192| 214| 144| 41 | 793 | 1155| 1144| 795 |
|11 | 163| 223| 244| 165| 42 | 814 | 1186| 1174| 816 |
|12 | 184| 254| 274| 186| 43 | 835 | 1217| 1204| 837 |
|13 | 205| 285| 304| 207| 44 | 856 | 1248| 1234| 858 |
|14 | 226| 316| 334| 228| 45 | 877 | 1279| 1264| 879 |
|15 | 247| 347| 364| 249| 46 | 898 | 1310| 1294| 890 |
|16 | 268| 378| 394| 270| 47 | 919 | 1341| 1324| 921 |
|17 | 289| 409| 424| 291| 48 | 940 | 1372| 1354| 942 |
|18 | 310| 440| 454| 312| 49 | 961 | 1403| 1384| 963 |
|19 | 331| 471| 484| 333| 50 | 982 | 1434| 1414| 984 |
|20 | 352| 502| 514| 353| 51 | 1003| 1465| 1444| 1005|
|21 | 373| 533| 544| 375| 52 | 1024| 1496| 1474| 1026|
|22 | 394| 564| 574| 396| 53 | 1045| 1527| 1504| 1047|
|23 | 415| 595| 604| 417| 54 | 1066| 1558| 1534| 1068|
|24 | 436| 626| 634| 438| 55 | 1087| 1589| 1564| 1089|
|25 | 457| 657| 664| 459| 56 | 1108| 1620| 1594| 1110|
|26 | 478| 688| 694| 480| 57 | 1129| 1651| 1624| 1131|
|27 | 499| 719| 724| 501| 58 | 1150| 1682| 1654| 1152|
|28 | 520| 750| 754| 522| 59 | 1171| 1713| 1684| 1173|
|29 | 541| 781| 784| 543| 60 | 1192| 1744| 1714| 1194|
|30 | 562| 812| 814| 564|    |     |     |     |     |
As can be seen from table 1, the critical edge for increasing the dynamic maximum flow of the network in the first 30 minutes is (2, 9), with the dynamic maximum flow value being the largest at any time in the 0-30min period after the expansion of (2, 9). But the critical edge of the flow increase in the next 30 minutes is (3, 4), and the expansion of the capacity can make the flow value at any time in the 31-60min period the largest. The expansion of the capacity of (4, 6) has little effect on the maximum flow, with an increase of only 2%. The expansion of the other edges has less effect on the dynamic maximum flow. Therefore, if the evacuation can be completed within 30 minutes, the corresponding link of (2, 9) can be expanded by reverse management. If the evacuation takes 60 minutes, the corresponding link of (3, 4) should be expanded within the next 30 minutes. The actual application can also be adjusted in combination with the specific evacuation demand and the emergency management resources, and the key is to select the most suitable road link for expansion in the corresponding time period.

4.3. Simulation analysis

In order to further analyze the influence of dynamic reverse management scheme on evacuation efficiency, it is necessary to describe the traffic state of the new network after expansion considering the dynamic characteristics of traffic flow. Through the traffic assignment model based on simulation proposed by the author in another paper[18], the evacuation traffic demand is assigned to the original road network and the new road network with capacity expansion scheme respectively, and the effects of different schemes are compared by calculating the overall evacuation time.

Assuming an evacuation demand of 600 pcu and 800 pcu at source point 2, 3, respectively, we used three reverse expansion schemes, as follows:

- Scheme 1: expand the capacity of the link (2, 9) throughout the whole period;
- Scheme 2: expand the capacity of the link (3, 4) throughout the whole period;
- Scheme 3: expand the capacity of the road section (2, 9) in the first 30 minutes, and expand the capacity of the section (3, 4) within the follow-up time. The evacuation time under each expansion scheme is shown in figure 2.

![Figure 2](image)

Figure 2. Comparison of evacuation time under each scheme

We can see from Figure 4 that no matter which expansion scheme is chosen, the evacuation time can be reduced to varying degrees compared with the original network, in which the evacuation time can be reduced by about 10 minutes for a single section (such as section (2, 9) or (3, 4), while the evacuation time can be reduced by 19 minutes for the dynamic expansion scheme.

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