Vehicle routing for incremental collection of disaster information along streets ⋆

Yuga Maki, Wenju Mu, Masahiro Shibata, and Masato Tsuru

Kyushu Institute of Technology, 680 Kawazu, Iizuka 820-8502, Japan
{maki.yuga692,wenju.mu142}@mail.kyutech.jp
{shibata,tsuru}@csn.kyutech.ac.jp

Abstract. When a large-scale disaster occurs, it is necessary for an emergency response headquarters (HQ) to promptly collect disaster damage information. We consider monitoring such information along all streets in a town by a single vehicle equipping cameras, mics, and other sensors especially when high-speed communications infrastructures are unavailable. The vehicle starts from HQ, cruises through all streets, and finally backs to HQ to bring monitored information. Note that the vehicle can return to HQ on the way to drop a partial information monitored before. In this paper, a vehicle routing problem is posed for the information collecting vehicle by considering not only collection time of the entire information but also how much ratio and how long time the information is delayed in incremental collection to HQ for an early decision and a partial response. A grid map is used as a town's street network with three types of HQ location. Through an extensive search by leveraging Eulerian circles, we found good routes for incremental collection of disaster information. The experimental results suggest the importance of an appropriate number of returns to HQ with almost equally-sized intervals depending on the HQ location.

Keywords: Vehicle routing · Disaster information collection · Eulerian circle.

1 Introduction

The increasing number of large-scale disasters such as earthquakes, typhoons and rainstorms in recent years has prompted an increasing concern and attention to the multifaceted impacts of large-scale natural disasters. An emergency response headquarters (HQ) is set up in or near the disaster area. It should collect the information on all areas and know the existence and extent of damage in a timely and accurate manner in order to make a better decision and response based on the collected information. For information collection, it is often considered to use vehicles that equip cameras, mics, and other sensors and cruise through all streets in a town to monitor the disaster damage situation around each street.

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In this paper, we assume that global and regional high-speed communications infrastructures are down or unavailable. In such conditions, the information collection vehicle should move not only to monitor the damage information along streets but also to bring that information to HQ by itself. As the simplest case, we use only a single information collection vehicle that starts from HQ and finally comes back to HQ. The vehicle should traverse every street at least once on the entire traveling route. On the other hand, it can return to HQ multiple times on the way of the route, drop the information monitored along the streets passed by that time, then depart from HQ again to cruise through the remaining streets. Multiple returns to drop the information for a part of all areas/streets to HQ is essential for making an early decision and a partial response.

We model the street map in a town as an undirected connected network graph. A HQ is located at a node of the network and is identically treated as that node. If the HQ has k links, the vehicle needs to return to HQ at least $\lceil k/2 \rceil$ times to cover those k links.

We focus on finding a good traveling route for an information collecting vehicle starting from and ending at HQ. This can be considered as a kind of Arc Routing Problem in Vehicle Routing Problem (VRP) [1]. However, in contrast to conventional VRPs where the shortest collection time is often pursued, we consider another evaluation criterion that represents how much ratio and how long time the disaster damage information is delayed in being brought to HQ by the vehicle. More precisely we use the following two criteria:

- Last information delay-time (LID):
  This is the time the vehicle finally comes back to HQ after traveling all links.
- Information delay-time product (IDP):
  Let $u(t)$ be the ratio of the information brought to HQ by the vehicle until time t, where t is the time spent from the vehicle's starting. The IDP is defined as $\displaystyle\int_0^{\mathrm{LID}} (1 - u(t))dt$.

A small IDP can benefit an early decision and a partial response by HQ, which is expected to be realized by an appropriate number of multiple returns of the vehicle to HQ. To make "LID" small, the traveling route should be as short as possible. However, to make "IDP" small, it is not always true. Furthermore, even in the simplest case, i.e., as Eulerian m-balanced decomposition problem (a decomposition of an Euler graph to multiple balanced Euler graphs), finding a route is shown to be NP-complete [2].

Please note, for simplicity, the following two assumptions are adopted.

- The unit time is taken for the vehicle to pass through each link in one direction. In other words, the number of links passed by the vehicle is equal to the time taken for the vehicle's travel. Hence the LID is longer than or equal to the number of links of the graph.
- The amount of information monitored by the vehicle is proportional to the number of different links passed through by the vehicle. Hence, $u(t)$ is the ratio of the number of different links passed by the vehicle before returning to HQ by time t to the total number of links of the entire network.

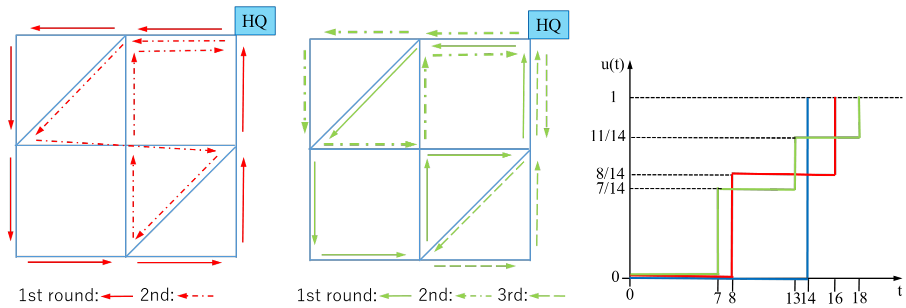

Fig. 1. A two-round route (left), a three-round route (center), and the time evolution of how much the information has been collected by HQ at t on each route (right).

2 Small example

Suppose a street network consisting of 14 links shown in Fig. 1. There are a variety of Euler circles each of which is a shortest route to cover all links. On this example network, we fix the location of HQ where the HQ has only 2 links. Therefore, on any Euler circle route, the vehicle comes back to HQ exactly once at time 14 to bring all link information in the entire network at once.

We also consider multi-round routes although they cannot be Euler circles anymore. A round is a portion (of a route) starting and ending at HQ exactly once. On the left and center sides of Fig. 1, a two-round route and a three-round route are indicated by red and green, respectively. On the two-round route, the vehicle firstly returns to HQ at time 8 to drop a partial information and finally returns to HQ at time 16 to bring the remaining information. On the three-round route, the vehicle returns to HQ on the way at times 7, 13, and 18, to drop a partial information, respectively.

For any shortest single-round route, the above two-round route, and the above three-round route, the LIDs are 14, 16, and 18, respectively, that is in ascending order. On the other hand, computed by the blue, red, and green step functions on the right of Fig. 1, the IDPs of those routes are 14, $\dfrac{80}{7} \approx 11.43$, and $\dfrac{155}{14} \approx 11.07$, respectively, that is in descending order. This example suggests a partial drop of monitored information to HQ on the way can reduce the IDP even with a longer LID.

Note that it can be mathematically proven that $80/7$ and $155/14$ are the lower-bounds of IDP of any two-round route and any three-round route on this example (in terms of network and HQ location), respectively. For those good, we also see that the entire route is decomposed into well-balanced multiple rounds in length. Furthermore, the IDP of $155/14$ is the minimum value among all possible any-round routes on this example.

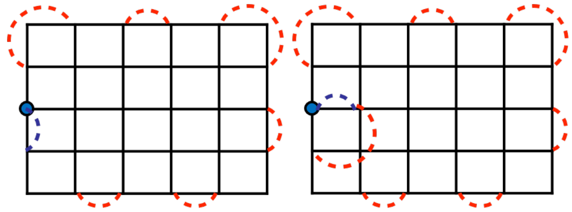

Fig. 2. Adding virtual links; two examples in case of $R = 2$ for HQ with 3 links.

3 Searching a good route

Given an undirected connected network graph G with a HQ location (node) on it, we find good routes in terms of LID and IDP. For this purpose, we generate a variety of routes starting and ending at HQ and traversing all links on G.

Let k be the number of HQ's links. The number R of vehicle's returns to HQ is set as a parameter of routing. The return times R should be equal to or greater than $\lceil k/2 \rceil$. For a given R,

(1) add some $(2R - k)$ virtual links between HQ and its neighboring nodes on G as links used for each return of the vehicle. We can control the return times R of vehicle by adding appropriate virtual links connecting to HQ. The blue link in Fig. 2 shows such a virtual link in case of $R = 2$ for HQ with 3 ($k = 3$) links. There are choices of locations of such virtual links to add.

(2) Then add necessary virtual links to make the entire graph an Eulerian graph (i.e., to make the degree of each node even) by bridging a pair of odd-degree nodes. The red links in Fig. 2 show such a set of the virtual links. This is the same approach as Chinese Postman Problem [3]. We also have choices of the bridging pairs of odd-degree nodes and the virtual links to bridge them. Note that the number of necessary virtual links in (2) depends on the locations of links added in (1) as shown by two examples in Fig. 2.

The obtained Eulerian graph G' including virtual links is used to construct a vehicle's route that cover all (original) links, i.e., links on G, efficiently. On graph G', we can find an Eulerian circle on which the vehicle returns to HQ R times, i.e. a R-round route. There also are choices of such an Eulerian circle.

We change the above-mentioned choices to generate a variety of R-round routes for a given R; then select good candidates in terms of given evaluation criteria. Finally we repeat this process for different Rs to find good (best) routes.

4 Experimental results

A 6×5 grid map is used as a town's street network for disaster information collection. There are 49 links and 30 nodes. Three types of HQ location are examined; the vertex (of the entire rectangle) with 2 links, the edge with 3 links, and the center with 4 links.

First, we consider the HQ location at the vertex with 2 links (k=2) shown in Fig.3 (top-left). The $u(t)$s of five exemplified routes on which the vehicle returns to HQ twice ($R = 2$) are shown in Fig.3 (top-right). All routes have the same LID, while the IDPs are different by routes; case 3's IDP is the smallest. Figure 3 (bottom-left) illustrates the exact route of the best case 3. The $u(t)$s of five exemplified routes on which the vehicle returns to the HQ three times ($R = 3$) are also shown in Fig.3 (bottom-right). For $R = 3$, the best route is also case 3 where the IDP is minimized and the LID is unchanged among the five. In those two good route examples for $R = 2$ and $R = 3$, we can see that the lengths of the rounds are well-balanced, i.e., the intervals between the succeeding returns to HQ are almost equalized.

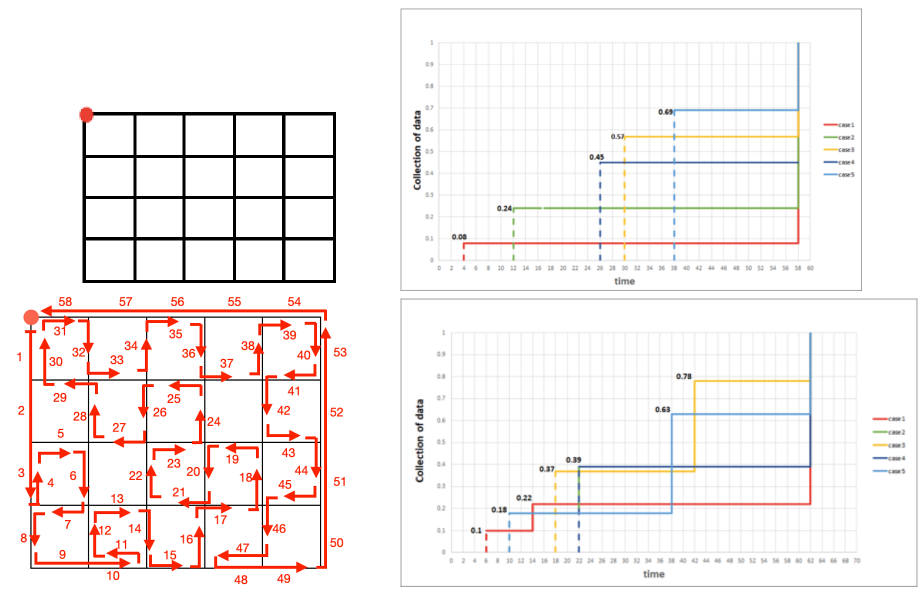

Fig. 3. HQ at a vertex (top-left); five cases of $u(t)$ for $R = 2$ (top-right); a best route for $R = 2$ (borrom-left); five cases of $u(t)$ for $R = 3$ (bottom-right).

Figure 4 compares the performance of ten good example routes for different Rs and in three types of HQ location. Regardless of the HQ location, we found that the LID is increased (at least not decreased) as the number R of the vehicle's returns to the HQ is increased. This is because the multiple returns increase duplicated traverses on the links connecting to HQ (blue links in Fig. 2 in Sec. 3) and at least it cannot decrease the number of duplicated traverses in total (blue and red links in Fig. 2). We also found that an appropriate number R of multiple returns to HQ can reduce the route's IDP. The best Rs in terms of IDP are 2, 3, and 5 when the HQ is located at the vertex, edge, and center, respectively. However, in case of HQ at the center, the IDPs of the best routes for $R = 3$ and $R = 5$ are almost the same while the LID of $R = 5$ is too large.

As a result, by considering the good balance between IDP and LID, $R = 2$, 3, and 3 are the good numbers of returns when the HQ is located at the vertex, edge, and center, respectively. Comparing the three types HQ location, we can adopt either the good case route for $R = 2$ with HQ at the vertex (LID is 58, the smallest; IDP is 42) or the good case route for $R = 3$ with HQ at the edge (LID is 60; IDP is 40.6, relatively small) as the best option of the HQ location and the number of returns.

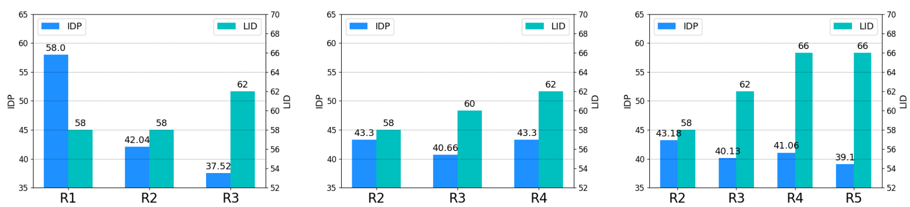

Fig. 4. IDP/LID of good cases for each R; HQ at vertex, edge, center (left to right).

5 Conclusion

A vehicle routing problem is considered in which a single information collection vehicle starts from an emergency response headquarters (HQ), cruises through all streets in a town to monitor the disaster damage situation, and finally backs to HQ to bring monitored information. On a grid map with different types of HQ location, traveling routes are investigated by considering a new criterion representing how much ratio and how long time the information is delayed in incremental collection. The experimental results suggest the importance of an appropriate number of returns to HQ with almost equally-sized intervals.

The future work could include (i) the use of multiple collaborating vehicles, (ii) the existence of uncertainty about street blocking, and (iii) the selection on a good HQ location in a deterministic or probabilistic sense.

References

1. Paolo Toth, Daniele Vigo (ed.), "The Vehicle Routing Problem," SIAM Discrete Mathematics and Applications, 2002.
2. Shuta Ishii, et al. "The complexity of Eulerian k-Balanced Decomposition," Proc. the 74th JCEEE in Kyushu, 2021. (in Japanese)
3. Martin Grotschel, Ya-iang Yuan, "Euler, Mei-Ko Kwan, Konigsberg, and a Chinese Postman," Documenta Mathematica: Optim. Stories, pp.43–50, 2012.