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Network-level optimization method for road network maintenance programming based on network efficiency

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Abstract: To maintain their capacity, transportation infrastructures are in need of regular maintenance and rehabilitation. The major challenge facing transportation engineers is the network-level policies to maintain the deteriorating roads at an acceptable level of serviceability. In this work, a quantitative transportation network efficiency measure is presented and then how to determine optimally network-level road maintenance policy depending on the road importance to the network performance has been demonstrated. The examples show that the different roads should be set different maintenance time points in terms of the retention capacities of the roads, because the different roads play different roles in network and have different important degrees to the network performance. This network-level road maintenance optimization method could not only save lots of infrastructure investments, but also ensure the service level of the existing transportation system.

Key words: transportation network; maintenance policy; network efficiency; time point; sensitivity analysis

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1 Introduction

Transportation networks play an important role in critical infrastructures underpinning the societies and economies. The mushroom developments of the transportation infrastructure constructions have made transportation networks improve dramatically in China in recent years, which has effectively propelled the developing of our societies and economies. But as time goes on, more and more diseases of pavement begin to be shown. According to the statistics from the Ministry of Transport of the People's Republic of China [1], by the end of 2013, there were total 4356200 km roads (including 104400 km highway) in China, in which 4251400 km (nearly 97.6%) should be maintained. It is estimated that these maintenance programs will result in approximately ¥84 billion Chinese yuan in terms of needed repairs for roads. So, the road maintenance policies that could extend the lifetimes of the pavements and ensure the service level of the transportation networks are the growing problem in China.

In the practice, the dominant factor determining whether the road should be repaired is the condition of single road. In other words, if the capacity of a road is degraded to a given level, then this road should be repaired or rehabilitated, which is a typically "treatment" method with hindsight. These policies are determined by the conditions of the single road, but not the performance of the network. It's well-known that the different roads play different roles in the transportation network, and the infrastructures of the transportation network are always not independent. According to the traffic theory [2], the change of condition of any infrastructure will cause the change of the traffic distribution in whole network, which will affect the role and the importance of each road in the network. So, we should not make the decision based on the separate road condition and use the same standards to identify which and when the road should be maintained.

With the development of the society, high quality road maintenance policies are required. The preventive maintenance policy is introduced to transportation engineering, which includes the care and servicing for the purpose of maintaining transportation infrastructures, such as roads and bridges, at an acceptable level of serviceability by providing for systematic inspection, detection, and correction of incipient failures either before they occur or before they develop into major defects. In other words, the road preventive maintenance

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method is predetermined work performed to a schedule with the aim of preventing the sudden failure of transportation network, which is the most effective way to change the current passive situation with social and economic benefit [3]. In the process of the preventive maintenance, because the works will be performed to maintain the roads which are still in satisfactory operation condition, the engineers always face a very difficult problem, which is to determine the time points that the roads or other infrastructures need to be serviced and repaired [4].

In existing studies, numerous mathematical methods have been applied to road maintenance problems. DURANGO and MADANAT [5] used the Markov decision problems to investigate the optimization for infrastructure maintenance and repair schedules considering uncertain deterioration rates. DONG et al [4] introduced some existing methods for determining the time point of the pavement maintenance. FENG et al [6] proposed a real-time optimization method to determine the vehicle dispatch schedule for winter road maintenance operations. YAO et al [7] and WANG et al [8] used various indexes of pavement performance to determine the optimal time point of asphalt pavement preventive maintenance. DURANGO-COHEN and SARUTIPAND [9] presented a quadratic method to find optimal maintenance polices for multi-facility transportation systems, in which the interdependency of demands and deterioration is considered. NODEM et al [10] optimized the policies of preventive maintenance and production for a degraded manufacturing system. WANG [11] proposed an optimization model of pavement preventive maintenance time point and countermeasures based on data envelopment analysis. GARZA and AKYILDIZ [12] presented a network-level pavement maintenance optimization model, in which the total lane-mile in each pavement condition state is considered. YU et al [13] proposed a life-cycle economic evaluation of the preventive maintenance practice on asphalt pavement. BROOMFIELD [14] developed a holistic approach to maintain the old bridge network; COSTELLO et al [15] proposed a new performance indicator—vehicle operating cost index, to determine the pavement maintenance decision. GUO et al [16] used the fuzzy mathematics approach to determine the sequences and methods of maintenance for rural road. CHEN and HOÀNG [17] studied optimization methods for the vehicle routing problem in daily maintenance of a road network.

Although the maintenance polices for transportation systems are widely studied, individual roads or facilities are not identified and are assumed to be homogeneous in the literature. As a result, optimal maintenance polices specify the same set of time point for all roads that are in a given state. The research into the network-level maintenance policy of transportation systems is still scare.

The rational road maintenance policies should be determined by the network performance, except for the condition of the single road. Transportation network efficiency comprehensively reflects the operation performance of transportation network, which represents the common-effect of traffic demand, travel costs and other factors on the network. If we could consider the feedback of the network efficiency in the process of maintenance decision-making, namely, the decision could be determined based on the network efficiency, it will no doubt help to increase the optimization and reliability of the road maintenance policy and plans. But there are few quantitative efficiency measures to be used in the optimization model. Many research considered a single index as the network efficiency [18–20]. LATORA and MARCHIORI [21] developed a method to measure network efficiency in which the links may have associated weights or costs. This method was used in many studies [21–26] related to complex network. For example, HSU and SHIN [27] used this methed to measure the airline network too. But the road congestion effects were not considered in this method, which resulted in invalidation in measuring of TNE. NAGURNEY and QIANG [28–29], QIANG and NAGURNEY [30] presented a quantitative efficiency evaluation method for transportation network, in which the parameters were only the number of OD pairs, path flows and path travel costs. The influence of the network scale on the efficiency is neglected. In this work, we will propose a new transportation network efficiency measure and a network-level method to determine optimally the road maintenance time point based on the efficiency measure.

Therefore, the well-known fixed demand network equilibrium model is recalled. The network efficiency measure and the sensitivity of the network efficiency to the road capacity are proposed, based on which the network-level method for determining the optimal maintenance time point of the road is presented. Finally, the method is applied to a network example.

2 Transportation network equilibrium model

We define the transportation network efficiency measure with the traffic parameters at equilibrium. In this section, the transportation network equilibrium model with fixed demands is recalled [31].

Consider a transportation network $G=(N, A)$, in which N is set of nodes and consists of n elements, A is set of roads with n_A elements. The W is the set of OD pairs of nodes with n_W elements. The set of paths connecting OD pair $w \in W$ is denoted by K_w. The demand for OD pair w is denoted by q_w. And we assume that the demand q_w is known for all $w \in W$. The flow and the travel cost on road $a \in A$ are x_a and $t_a = t_a(x_a)$, respectively. The flow on path is denoted by f_k^w.

The indicator variable $\sigma_{a,k}^w$ is set as

$$\sigma_{a,k}^w = \begin{cases} 1, & \text{if link } a \text{ is on path } k \text{ connectting } OD \text{ pair } w \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

In this work, we will consider user road travel time functions known as Bureau of Public Road (BPR) functions, given by

$$t_a(x_a) = t_a^0 \left(1 + a \left(\frac{x_a}{c_a} \right)^{\beta} \right) \tag{2}$$

where t_a^0 is the free-flow travel time or cost on road a; x_a is the flow on road a; c_a is the capacity of road a, which also has the interpretation of the level-of-service flow rate; α and β are the model parameters and both take on positive values. Often in applications α=0.15 and β=4.

The equilibrium road flow can be obtained by solving the flowing fixed demand traffic equilibrium model [31]:

$$\min \sum_{a \in A} \int_0^{x_a} t_a(y)\mathrm{d}y \tag{3}$$

$$\text{s.t.} \sum_{k \in K_w} f_k^w = q_w,\ \forall w \in W \tag{4}$$

$$x_a = \sum_{w \in W} \sum_{k \in K_w} f_k^w \sigma_{a,k}^w,\ \forall a \in A \tag{5}$$

$$f_k^w \geq 0,\ \forall w \in W,\ \forall k \in K_w \tag{6}$$

In this model, the objective function (Eq. (3)) is to minimize the total travel cost in the network. This function does not have any intuitive economic or behavioral interpretation, which should be viewed as a mathematical construct that is utilized to solve equilibrium problems. Equation (4) represents a set of flow conservations, which means that the sum of flows on paths connecting each OD pair w must be equal to the demand for OD pair. In other words, all OD demands have to be assigned to the network. The road flows are related to the path flows through the conservation of flow Eq. (5). Equation (6) are the nonnegative constraint on path flows, which ensures that the solution of the model will be physically meaningful.

There are many algorithms for the solutions of the above model (Eqs. (3)–(6)), such as Frank-Wolfe (FW) method, Gradient projection (GP) method. This work does not focus on the solution method, so the classical GP method is selected here to solve the above model. The details of the GP method can be found in Ref. [32].

3 Network-level maintenance policy

3.1 Transportation network efficiency measure

To the author's knowledge, quantitative efficiency measure for transportation network is quite rare, especially that can be applied to transportation network efficiency.

LATORA and MARCHIORI [21] proposed the "global efficiency" to evaluate the network performance in a weighted network. The method could be recalled as

$$E_{\mathrm{LM}} = \frac{1}{n(n-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \tag{7}$$

where E_{LM} is the global efficiency; a_{ij} is the travel time (the shortest path length) between the node i and node j at equilibrium.

Considering the congestion effects on roads in transportation network, the lengths of the shortest paths between two nodes change with the traffic demands. And the shortest path lengths are bound to increase with the growth of the demands in the transportation network. But according to Eq. (7), the efficiency E_{LM} is a monotone decreasing function of demands. In this way, the efficiency E_{LM} will reach the maximum when the traffic flows on all roads are 0. Of course, it is unreasonable. Therefore, measuring and analyzing the network efficiency with Eq. (7) may lead to misleading results.

NAGURNEY and QIANG [28] presented an efficiency measure for transportation network, which could be recalled as

$$E_{\mathrm{NQ}} = \frac{1}{n_W} \sum_{w \in W} \frac{q_w}{\lambda_w} \tag{8}$$

where λ_w represents the travel time at equilibrium on the used path connecting OD pair w.

According to Eq. (8), we could find that the parameters are only the number of OD pairs n_w, traffic demands $q_w, w \in W$ and path travel costs $\lambda_w, w \in W$. The effects of network scale on the network efficiency E_{NQ} are neglected.

For example, consider the simple transportation network only with two nodes (Fig. 1), in which we assume that the travel times on all paths connecting the two nodes and the OD demand between the two nodes all are constant, ie, λ and q. Then according to Eq. (8) we could know that the efficiency E_{NQ} is a constant q/λ, which is independent of the number of the paths. Furthermore, even if the travel times on all paths are computed by BPR functions, we also could find that the efficiency E_{NQ} will be the monotonic increasing function of the number of the paths connecting the nodes. This does not accord with the actual situation of the transportation network performance.

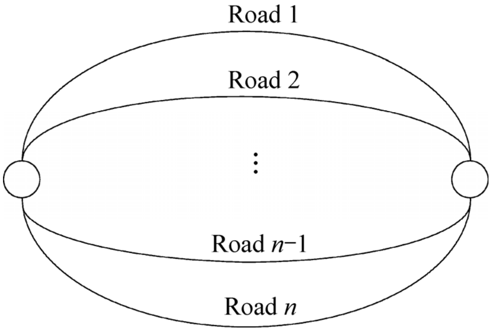

Fig. 1 A simple network

Based on the above analysis, we could know that the existing quantitative efficiency measures for transportation network can not reflect the integral effect of the multi-factors in the network. In other words, the reasonable transportation network efficiency measure must be able to report the combined influence of traffic demands, travel cost, behavior of users and network structure/scale on the network performance.

It is well-known that the road flows at equilibrium are the results of the interactions between the above factors, which represent the usage of a network. In addition, the travel costs on the roads are also important indicators which can help to evaluate the operation status of transportation network. As a result, the flows and the travel costs on the roads at equilibrium can be considered the main indicators to calculate or quantitatively evaluate the transportation network efficiency.

Here, we propose a quantitative transportation network efficiency measure, which is defined by the traffic flows and road travel times at equilibrium as follows:

$$E=E(G,q)=\frac{1}{n_A}\sum_{a\in A}\frac{\bar{x}_a}{\bar{t}_a} \tag{9}$$

where E is the network efficiency; $\bar{x}_a$ and $\bar{t}_a$ are the flow time and equilibrium travel time at equilibrium on road a, respectively.

The efficiency measure method (Eq. (9)) has a good economic interpretation, since it evaluates the average operation efficiency/performance (road-based) of transportation network from the perspective of the economic costs (travel time). This means that the efficiency can be understood as the average traffic volume to travel time ratio with the equilibrium flow on road a given by $\bar{x}_a$ and the equilibrium travel cost on road a by $\bar{t}_a$. The effect of the network scale on the network efficiency is measured by n_A. It is clear that the more the traffic demands that the network can be served at a certain travel cost (travel time) are, the higher the transportation network performance is.

3.2 Maintenance policy based on network efficiency sensitivity

The transportation network efficiency reports the common-effect of kinds of factors on the network performance, and the network-level maintenance policy could be determined based on the network efficiency. Then, according to the network efficiency measure Eq. (9) we define the sensitivity of network efficiency to the road capacity in a transportation network as follows.

The sensitivity measure for a transportation network $G=(N, A)$ on the degradation of road $a\in A$ is defined as the relative performance retained under a given capacity retention ratio δ with $0<\delta\le 1$ of road a. In other words, for the road a with original capacity c_a, and the original network efficiency is E. When the other parameters of the network remain unchanged, the capacity of road a degrades to δc_a ($0<\delta\le 1$), then the network efficiency changes to E_a^δ. The sensitivity of network efficiency to capacity of road a is the ratio of the relative change of efficiency E to the relative change of capacity of the road a.

The mathematical definition of the sensitivity of the network efficiency to the capacity of road a is given as

$$\eta_a^\delta=\frac{E-E_a^\delta}{E}\Big/\delta=\frac{E-E_a^\delta}{\delta E} \tag{10}$$

where E and E_a^δ are the network efficiency measures with the original capacity and the remaining capacity of road a respectively. For example, if δ=0.8, this means that the user road travel time on road a given by Eq. (2) now has the road capacity given by $0.8c_a$; if δ=0.5, then the road capacity of road a is $0.5c_a$.

From the above definition, for a transportation network, under a given uniform level of capacity retention to all roads in the network, the roads that their sensitivity values are higher are considered to be more important.

For the maintenance policy, we could get the curve of the sensitivity η_a^δ when the parameter δ changes continuously. In general, if the value of η_a^δ reaches the given level θ, namely, $\eta_a^\delta\ge\theta$, it means that the minor change of the capacity of road a will result in the great change of the network operation performance, then we could know that the road a needs to be maintained, repaired or rehabilitated.

To summarise, the above efficiency sensitivity method could determine the optimal maintenance policy depending on the road importance to the network performance, but not on the condition of single road. And this network-level management considers the entire network by network efficiency measured by Eq. (10), which captures the demands, travel cost, user behaviors and network structure/scale.

4 Numerical examples

4.1 Simple network example

Considering the transportation network in Fig. 2, in which there are 5 OD pairs: (1, 2), (1, 4), (1, 3), (3, 2) and (3,4). The traffic demands are given, respectively, by q_{12}=16, q_{14}=24, q_{13}=6, q_{32}=11, q_{34}=8.

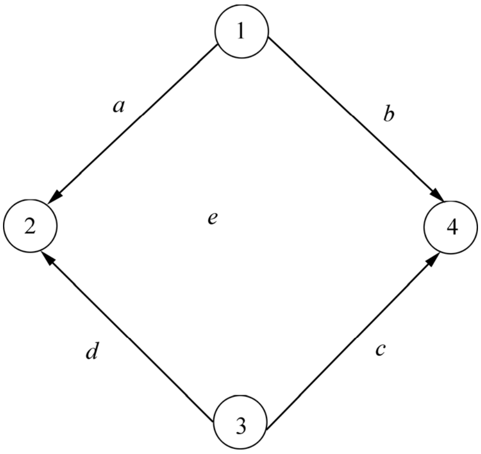

Fig. 2 Simple transportation network

As mentioned before, we assume the road travel cost functions known as Bureau of Public Road (BPR) functions, given by

$$t_a(x_a)=10\left[1+0.15\left(\frac{x_a}{8}\right)^4\right] \tag{11}$$

$$t_b(x_b)=15\left[1+0.15\left(\frac{x_b}{16}\right)^4\right] \tag{12}$$

$$t_c(x_c)=9\left[1+0.15\left(\frac{x_c}{24}\right)^4\right] \tag{13}$$

$$t_d(x_d)=10\left[1+0.15\left(\frac{x_d}{20}\right)^4\right] \tag{14}$$

$$t_e(x_e)=6\left[1+0.15\left(\frac{x_e}{32}\right)^4\right] \tag{15}$$

The GP method is utilized to compute the road flows at equilibrium as

$$\begin{aligned}x&=(\bar{x}_a,\bar{x}_b,\bar{x}_c,\bar{x}_d,\bar{x}_e)\\&=(11.6399, 12.3698, 19.6303, 15.3602, 21.9904)\end{aligned}$$

Meanwhile, the network efficiency E=1.7058.

4.1.1 Network efficiency measure

In order to investigate the advantages of our efficiency measure, we will illustrate that how the efficiency values change with the OD demands.

Figure 3 shows that when the OD demand q_{14} ranges from 1 to 200 (the other demands remain unchanged), the efficiency values E fluctuate with q_{14} before and after removing road b, respectively. We could find that demand and the network structure/scale all have an impact on the network performance. The efficiency E has extreme points when the demands are changing, no matter whether the road b is removed or not. Of course, the points are different before and after removing the road b. This is due to the fact that a transportation network with fixed scale/structure always has an optimal service traffic volume. In other words, it is inappropriate for a given transportation network in which the total traffic volume is too much or too little. We believe that the capacities of the transportation infrastructures are wasted when the traffic volume is too little. Conversely, if the traffic volume is too much, the congestion will be caused and the travel time will increase. But with the consistent growth in traffic, the gap between the efficiency values before and after removing the road gradually narrows.

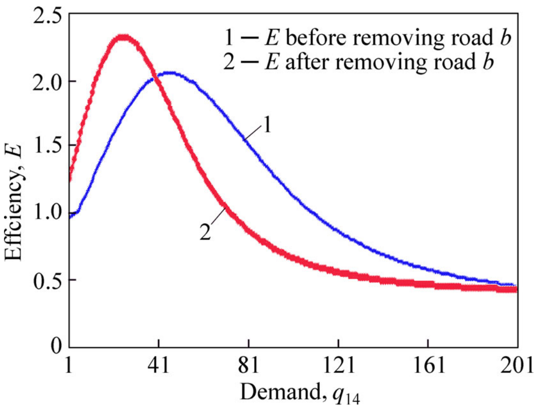

Fig. 3 q_{14} vs E in simple network

In Fig. 3, the efficiency value E fluctuates with the change of demand q_{14}, and there are two extreme points before removing road b, while only one after removing the road. The reason is that there are two connected paths (road b and road e+c) between (1, 4) before removing road b, while only one path (road e+c) after removing the road. Obviously, it is consistent with the objective law of transportation network operation.

We can see from Fig. 3 that sometimes the efficiency value E after removing road b is bigger than that before removing it. For example, when q_{14}=14, efficiency values are 1.3627 and 2.5555 before and after removing road b, respectively, which indicates that the addition of road b actually makes all users in the network worse off without the road b, and the total travel time is 43.5834, whereas with the new road b, the total travel time rises to 57.4879. It is known as Braess Paradox in the transportation network [34]. Moreover, in Fig. 2 it is clear that the situation takes a fundamental shift when the q_{14}>41, which is in conformity with the conclusions in

Ref. [35] that the Braess Paradox only occurs in a certain part of demand range.

From the above analysis, the scientifiity in theory and feasibility in practice of the transportation network efficiency measure Eq. (8) have been proved. The example showed that the method not only measures the performance of the transportation network objectively, but also reflects how demands, travel cost, travel choice and network structure/scale affect the network performance.

4.1.2 Efficiency-oriented road maintenance policy

With Eq. (10), when the capacity retention rate of each road δ changes from 1 to 0.1 continuously, we could get the sensitivity curves of network efficiency to each road capacity, as shown in Fig. 4.

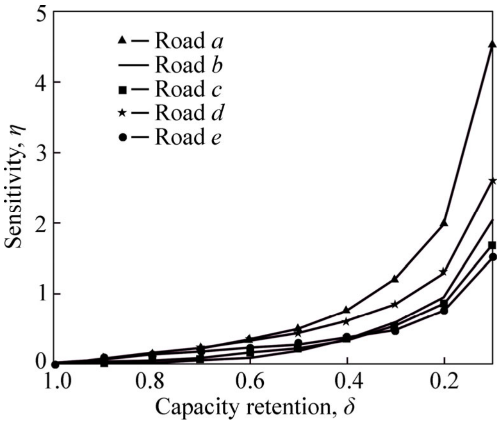

Fig. 4 Capacity retention δ vs. sensitivity η in simple network

In Fig. 4, we see that for a given capacity retention ratio, when the value of δ is large, the sensitivity value η, ie the network efficiency to the road capacity, increases less severely than that when δ is small. It is clear that for the roads, sensitivity risen faster is more important to the network performance. Then, from the figure it is clear that the road imortance ranking in descenching order is Road *a*> Road *d*> Road *b*> Road *c*> Road *e*. So, the roads *a* and *d* should be monitored and maintained more carefully.

If we assume that the road must be maintained and rehabitated its capacity when the sensitivity value η=0.5. From Fig. 2, we could know that when δ_a=0.50, δ_b=0.35, δ_c=0.32, δ_d=0.49, δ_e=0.31, the roads *a*, *b*, *c*, *d* and *e* should be rehabitated respectively. For example, when δ_b=0.32 the remaining, capacity of road *b* is $\delta_b c_b$= 0.35×16=5.6, which means that when the capacity of road *b* degrades to below 5.6, the minor change of the capacity of road *b* will make great drops of the netrwork efficiency, and then preventive maintenance activities need to be taken in order to maintain the capacity retention of road *b* above the level. But for road *a*, it needs to be maintained when its capacity degrades to the point as $\delta_a c_a$=0.5×8=4. This is due to the fact that the influences of the drops of road capacities on the network performance reach the maximum permissible level in these capacity points(refer as maintaneance point).

We could also find in the figure that the greater the road capacity is, the earlier the maintaneance time point of the road is. It is because the roads with greater capacities have more slack/reduntant capacities available when roads in the network are subject to partial degradation.

From the above analysis, we could know that the different roads can be set different maintenance points in the transportation network because the different roads have different important degrees to the operation efficiency of the whole network. So, it was completely unnecessary to set the the same maintenance point to all roads in the network, which could save lots of maintenance and construction funds without great negtive influence on the network operation.

These results also has implication for transportation network policy-making and planning. An effictive and economic policy for road maintenance should keep the network robustness above a certain critical value.

4.2 Complex network examples

We now consider the network in Fig. 5. There are 12 nodes and 17 roads. The parameter $t_a^0(c_a)$ of each road is labeled under the link. The only demand is given by $q_{1,12}$=10.

Form Fig. 6, we could see that the efficiency E in

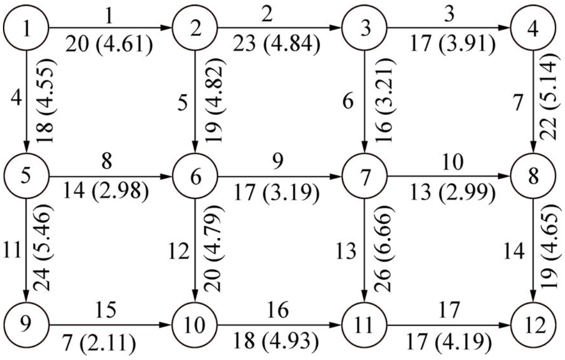

Fig. 5 Complex transportation network

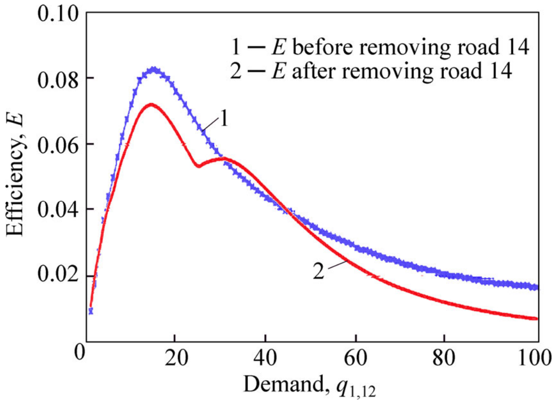

Fig. 6 $q_{1,12}$ vs E in complex transportation network

the complex transportation network also changes with the demand $q_{1,12}$, which is similar to Fig. 3.

We investigated the senstivity values of all roads to the network efficiency in the complex network.

From Fig. 7, it can be easily found that the sensitivity of each road is different, which is still similar to the simple network example. And we could determine that road 8 and road 17 are the mostly used roads in the complex network.

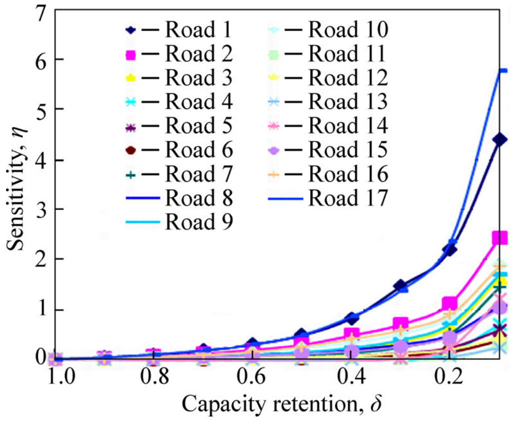

Fig. 7 Capacity retention δ vs sensitivity η in complex network

5 Conclusions

A new transportation network efficiency measure and a rigorous efficiency sensitivity measure are presented, which could reflect the effects of demands, travel cost, behavior of users and network structure/scale on the network performance and help engineers to determine the optimal network-level road maintenance policy respectively. The numerical examples demonstrate that the efficiency measure can report more realistic assessments of the performance of the transportation network, meanwhile the maintenance time point of each road is explicitly computed based on the efficiency sensitivity analysis. From the results, because different roads play different roles in the network, the maintenance time points of the roads could be set not to be same in a transportation network.

In the future, it would be very interesting to consider whether the methods could be applied to quick estimation of the network efficiency and sensitivity.

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